

Description

This invention relates to parallel computation networks.

Recently, advances in the computational circuits art have brought to the forefront a class of highly parallel computation circuits that solve a large class of complex problems in analog fashion. These circuits comprise a plurality of amplifiers having a sigmoid transfer function and a resistive feedback network that connects the output of each amplifier to the input of the other amplifiers. Each amplifier input also includes a capacitor connected to ground and a conductance connected to ground which may or may not include a capacitor and a conductor in addition to the parasitic capacitance and conductance. Input currents are fed into each amplifier input, and output is obtained from the collection of output voltages of the amplifiers.

Proceedings of the national academy of sciences of the US, volume 81, May 1984, pages 3088-3092; J.J. Hopfield: "Neurons with graded response have collective computational properties like those of two-state neurons", addresses the question of whether a neural network that possesses a linear gain function and operates in continuous time exhibits the same minima-seeking characteristics of a stochastically sampled network with ideal two-state threshold devices. This reference concludes that as long as the gain of the amplifiers is high enough, the two networks exhibit the same characteristics.

The invention will be described with reference to the accompanying drawings, in which:

FIG. 1 shows a known highly interconnected analog network;

FIG. 2 illustrates part of one form of network embodying the invention, and

FIG. 3 illustrates part of another form of network embodying the invention.

Referring now to FIG. 1, amplifiers 10, 11, 12, 13 and 14 have positive and negative outputs V_1, V_2, V_3, V_4 , and V_N , respectively. Those outputs are connected to an interconnection block 20 which has output lines 41-45 connected to the input ports of amplifiers 10-14, respectively. Within interconnection block 20, each output voltage V_i is connected to each and every output line of block 20 through a conductance (e.g. resistor). For convenience, the conductance may be identified by the specific output line (i.e. source) that is connected by the conductance to a specific voltage line. For example, T_{21}^+ identifies the conductance that connects the non-inverting output V_2 to the input of the first amplifier (line 41).

Also connected to each amplifier input port is a parallel arrangement of a resistor and a capacitor (with the second lead of the resistor and capacitor connected to ground), and means for injecting a current into each input port (from some outside source).

Applying Kirchoff's current law to the input port of each amplifier i of FIG. 1 yields the equation:

$$C_i (du_i/dt) = - U_i/R_i + \sum_j (T_{ij}^+ - T_{ij}^-) (V_j - U_i) + I_i \quad (1)$$

where

C_i is the capacitance between the input of amplifier i and ground,

$$\frac{1}{R_i}$$

is the equivalent resistance and it equals

$$\frac{1}{R_i} + \sum_j \frac{1}{R_{ij}}$$

where R_i is the resistance between the input of amplifier i and ground,

U_i is the voltage at the input of amplifier i ,

T_{ij}^+ is the a conductance between the non-inverting output of amplifier j and the input of amplifier i ,

T_{ij}^- is the a conductance between the inverting output of amplifier j and the input of amplifier i ,

V_j is the positive output voltage of amplifier j , related to U_j by the equation $V_j = g_j(U_j)$, and

I_i is the current driven into the input port of amplifier i by an external source.

When T_{ij}^+ and T_{ij}^- are disjoint, $T_{ij}^+ - T_{ij}^-$ may for convenience be expressed as T_{ij} , and it is well known that a circuit satisfying equation (1) with symmetric T_{ij} terms is stable. It is also well known that such a circuit

responds to applied stimuli, and reaches a steady state condition after a short transition time. At steady state, $du/dt = 0$ and $dV/dt = 0$.

With this known stability in mind, the behavior of other functions may be studied which relate to the circuit of FIG. 1 and involve the input signals of the circuit, the output signals of the circuit, and/or the circuit's internal parameters.

Indeed, a function was studied that has the form

$$E = -\frac{1}{2} \sum_{i,j} T_{ij} V_i V_j + \sum_i (1/R_i) \int_0^{V_i} g_i^{-1}(v) dv - \sum_i I_i V_i \quad (2)$$

where $g_i^{-1}(v)$ is a function that is related to the gain of the amplifiers and is such that the integral of the function $g_i^{-1}(V)$ approaches 0 as the gain of amplifier i approaches infinity. Also, the time derivative of the function E is negative, and that it reaches 0 when the time derivative of voltages V_i reaches 0. Since equation (1) assures the condition of dV/dt approaching 0 for all i , the function E of equation (2) is assured of reaching a stable state. The discovery of this function E led to the use of the FIG. 1 circuit in problem solving applications in associative memory applications, and in decomposition problems.

The FIG. 1 circuit can solve problems which can be structured so that the function to be minimized has at most second order terms in some parameters of the problem to permit correspondence to Equation (2). Other problems, however, may require the minimization of equations that contain terms of order higher than two. Those problems are solvable through the use of interneuron amplifiers wherein the T_{ij}^+ and the T_{ij} are conductances that assume different values, which are a function of the problem to be solved. The different values, however, cause the circuit to behave differently in response to different stimuli because of the different time constants associated with each amplifier.

According to one aspect of this invention there is provided a network as claimed in claim 1.

According to another aspect of this invention there is provided a network as claimed in claim 2.

Superior performance is achieved by equalizing the time constants of the amplifiers. One technique employs a feedback arrangement where the resistance between the input of each amplifier i and ground, and the capacitor between the input of each amplifier and ground are, instead, connected in parallel between the input of each amplifier and its corresponding output. A second technique employs a balanced impedance arrangement where, for example, a zero current with a non-zero thevenin conductance is achieved by employing equal value T_{ij}^+ and T_{ij} conductances.

Referring again to FIG. 1, the circuit includes a capacitor and a resistor between each amplifier input and ground. The capacitor is the element that controls the time constant, or speed, of the circuit and in ordinary circuits it would behoove the designer to make the capacitor as small as practicable. The circuit, however, permits feedback to be established through what effectively is a series connection of a number of amplifiers. Without any capacitance in the circuit, instability would almost certainly occur. Even with capacitance in the circuit an instability condition could result except that, with selection of the T_{ij} conductances, stability is maintained.

There is an additional aspect to the presence of the capacitors. When the feedback paths to a particular capacitor of FIG. 1 are combined to appear as a single equivalent voltage and an equivalent resistance, R_e , it becomes readily apparent that a pole exists in the frequency domain. That pole derives from the voltage division action of the capacitor and its parallel resistor, yielding a gain equation for each amplifier that is related to $1/(1 + sCR_e)$. From this it is apparent that the pole position is a function of the feedback resistors and, therefore, we can expect different pole positions associated with different amplifiers in the FIG. 1 circuit. In turn, we should expect different speeds of response from the different amplifiers. What this means is that the circuit of FIG. 1 minimizes the energy function of Equation (2), but the manner in which it reaches this minimum is less than optimum since the slowest amplifier dictates the response time of the entire circuit.

The problem of different pole positions is obviated with the circuit of FIG. 2 where each capacitor (and its parallel resistor) is connected between its associated amplifier output and its negative input. The result is a virtual ground operation with an associated gain equation of $R/R_e(1 + sCR)$, where R is the resistor connected in parallel with the capacitor. That yields a fixed pole that is related solely to the capacitor and its parallel resistor. Correspondingly, the result is equal speeds of response to all of the amplifiers, and the fastest settling time of the circuit for a given capacitance value.

The problem of different pole positions is also obviated with the circuit of FIG. 3. Therein, amplifier 10 is shown with input capacitor 11 and an input resistor 12 connected between the input of amplifier 10 and ground. Also connected to the input of amplifier 10 are conductance pairs (T_1^+, T_1^-) , (T_2^+, T_2^-) , and (T_n^+, T_n^-) . Each pair (T_i^+, T_i^-) derives its input from the output of amplifier i , and the output impedance of the amplifiers is assumed to be negligible.

The prior art computations of the T_{ij} values yield either positive or negative T_{ij} terms of different magnitudes. Since the amplifier input nodes are essentially at zero voltage potential, a negative T_{ij} simply means that current flows out of the amplifier's input node. A positive T_{ij} means that current flows into the amplifier's input node. In the prior art, when a computed T_{ij} is negative, the neural network of FIG. 1 incorporates a T_{ij}^- element into the matrix. Correspondingly, when a computed T_{ij} is positive, the neural network of FIG. 1 incorporates a T_{ij}^+ element into the matrix. From this it can be seen that T_{ij}^+ and T_{ij}^- are disjoint; that is, either one or the other but not both appear at any one time.

Regardless of the required sign and magnitude of the computed T_{ij} , both the T_{ij}^+ and the T_{ij}^- conductances are included in the matrix, as shown in FIG. 3. The effective conductance presented to amplifier 10 by the conductance pair T_1^+ and T_1^- is $(T_1^+ + T_1^-)$ and that sum is arranged to be constant. Since that effective conductance is constant, e.g., K , the effective overall conductance presented at the input node of each amplifier is also constant, and that results in equal speeds of response for the amplifiers. On the other hand, the current that is actually flowing into each amplifier's input node must be different, as specified by the computed T_{ij} , and that current is equal to $(T_{ij}^+ - T_{ij}^-)$. That value, e.g., $+A$, can be obtained while maintaining the requirement that $(T_1^+ + T_1^-) = K$ by selecting the magnitude of T_1^+ to be equal $\frac{1}{2}(K + A)$ by the magnitude of T_1^- to be equal $\frac{1}{2}(K - A)$.

In situations where there are a large number of required zero currents flowing into the amplifier nodes, and it is more convenient to create conductances of magnitude K (rather than some value between K and 0), it may be useful to create $T_i^+ = T_i^- = K$ conductances at half of the amplifiers, and zero conductances at the other half of the amplifiers.

Claims

1. A network comprising a plurality of amplifiers A_i (10) each having an input at which there is developed an input voltage U_i and each developing a non-inverting output V_i and an inverting output $-V_i$, with both of said outputs being related to said input by a sigmoid function g_i , means for applying input current I_i to said input of each of said amplifiers A_i , a conductance network for connecting said positive and negative outputs to said inputs and comprising conductance values selected for the nature of the decisional operation for which it is intended to minimize the energy function

$$E = -\frac{1}{2} \sum_i \sum_j T_{ij} V_i V_j + \sum_i \frac{1}{R_i} \int_0^{V_i} g_i^{-1}(V) dV - \sum_i I_i V_i$$

where V_i and V_j are output voltages of said amplifiers A_i and A_j , respectively, T_{ij} is a conductance that relates the amplified input voltage of amplifier A_i , having a gain function $g(U_i)$, to the input of amplifier A_j , R_i is the equivalent resistance at said input of said amplifier A_i , and g_i^{-1} is the inverse of g_i , and CHARACTERISED BY means for equalizing the response speeds of said amplifiers, said means comprising a subnetwork associated with each of said amplifiers and connected between the input and the negative output of each of said amplifiers, said subnetwork comprising a parallel interconnection of a resistor (32) and a capacitor (31).

2. A network comprising a plurality of amplifiers A_i (10) each having an input at which there is developed an input voltage U_i , and each developing a non-inverting output V_i and an inverting output $-V_i$, with both of said outputs being related to said input by a sigmoid function g_i , means for applying input current I_i to said input of each of said amplifiers A_i , a conductance network for connecting said positive and negative outputs to said inputs and comprising conductance values selected for the nature of the decisional operation for which it is intended to minimize the energy function



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In situations where there are a large number of required zero currents flowing into the amplifier nodes, and it is more convenient to create conductances of magnitude K (rather than some value between K and 0), it may be useful to create $T_1^+ = T_1^- = K$ conductances at half of the amplifiers, and zero conductances at the other half of the amplifiers.

Claims

1. A network comprising a plurality of amplifiers A_i (10) each having an input at which there is developed an input voltage U_i , and each developing a non-inverting output V_i and an inverting output $-V_i$, with both of said outputs being related to said input by a sigmoid function g_i , means for applying input current I_i to said input of each of said amplifiers A_i , a conductance network for connecting said positive and negative outputs to said inputs and comprising conductance values selected for the nature of the decisional operation for which it is intended to minimize the energy function

$$E = -\frac{1}{2} \sum_i \sum_j T_{ij} V_i V_j + \sum_i \frac{1}{R_i} \int_0^{V_i} g_i^{-1}(V) dV - \sum_i I_i V_i$$

where V_i and V_j are output voltages of said amplifiers A_i and A_j , respectively, T_{ij} is a conductance that relates the amplified input voltage of amplifier A_j , having a gain function $g_j(U_j)$, to the input of amplifier A_i , R_i is the equivalent resistance at said input of said amplifier A_i , and g_i^{-1} is the inverse of g_i , and CHARACTERISED BY means for equalizing the response speeds of said amplifiers, said means comprising a subnetwork associated with each of said amplifiers and connected between the input and the negative output of each of said amplifiers, said subnetwork comprising a parallel interconnection of a resistor (32) and a capacitor (31).

2. A network comprising a plurality of amplifiers A_i (10) each having an input at which there is developed an input voltage U_i , and each developing a non-inverting output V_i and an inverting output $-V_i$, with both of said outputs being related to said input by a sigmoid function g_i , means for applying input current I_i to said input of each of said amplifiers A_i , a conductance network for connecting said positive and negative outputs to said inputs and comprising conductance values selected for the nature of the decisional operation for which it is intended to minimize the energy function



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where V_i and V_j are output voltages of said amplifiers A_i and A_j , respectively, T_{ij} is a conductance that relates the amplified input voltage of amplifier A_i , having a gain function $g(U_i)$, to the input of amplifier A_j , R_i is the equivalent resistance at said input of said amplifier A_i , and g_i^{-1} is the inverse of g_i , and CHARACTERISED BY means for equalizing the response speeds of said amplifiers, said means comprising a conductance T_{ij} with each conductance T_{ji} such that $(T_{ij} + T_{ji})$ is a constant and $(T_{ij} - T_{ji})$ is equal to said conductance T_{ij} , where T_{ji} is a conductance connected between output V_i of amplifier A_i and the input of amplifier A_j , and T_{ij} is a conductance connected between output $-V_i$ of amplifier A_i and the input of amplifier A_j .

Patentansprüche

1. Netzwerk mit einer Vielzahl von Verstärkern A_i (10), die jeder einen Eingang haben, an welchem eine Eingangsspannung U_i entwickelt wird, und die jeder ein nichtinvertierendes Ausgangssignal V_i und ein invertierendes Ausgangssignal $-V_i$ entwickeln, wobei beide Ausgangssignale mit dem Eingang durch eine Sigmoidfunktion g_i in Beziehung gesetzt sind, mit einer Einrichtung zum Anlegen eines Eingangsstroms I_i an den Eingang jedes Verstärkers A_i , einem Konduktanznetzwerk zum Verbinden der positiven und negativen Ausgänge mit den Eingängen und mit den Konduktanzwerten, die für die Natur der Entscheidungsoperation ausgewählt sind, bei welcher beabsichtigt ist, die Energiefunktion

$$E = -\frac{1}{2} \sum_i \sum_j T_{ij} V_i V_j + \sum_i \frac{1}{R_i} \int_0^{V_i} g_i^{-1}(V) dV - \sum_i V_i$$

zu minimieren, wobei V_i und V_j jeweils Ausgangsspannungen der Verstärker A_i und A_j sind, T_{ij} eine Konduktanz ist, welche die verstärkte Eingangsspannung des Verstärkers A_i , der eine Verstärkerfunktion $g(U_i)$ hat, mit dem Eingang des Verstärkers A_j in Beziehung setzt, R_i der äquivalente Widerstand an dem Eingang des Verstärkers A_i ist und g_i^{-1} das Inverse von g_i ist und gekennzeichnet ist

durch eine Einrichtung zum Ausgleichen der Antwortgeschwindigkeit der Verstärker, wobei die Einrichtung ein Subnetzwerk hat, das zu jedem Verstärker gehört und zwischen dem Eingang und dem negativen Ausgang jedes Verstärkers angeschlossen ist, wobei das Subnetzwerk eine parallele Verbindung aus einem Widerstand (32) und einem Kondensator (31) hat.

2. Netzwerk mit einer Vielzahl von Verstärkern A_i (10), von denen jeder einen Eingang hat, an welchem eine Eingangsspannung U_i entwickelt wird und jeder ein nichtinvertierendes Ausgangssignal V_i und ein invertierendes Ausgangssignal $-V_i$ entwickelt, wobei beide Ausgänge mit den Eingängen durch eine Sigmoidfunktion g_i in Beziehung gesetzt sind, mit einer Einrichtung zum Anlegen eines Eingangsstroms I_i an den Eingang jedes Verstärkers A_i , einem Konduktanznetzwerk zum Verbinden der positiven und negativen Ausgänge mit den Eingängen und mit Konduktanzwerten, die für die Natur der Entscheidungsoperation ausgewählt sind, bei welcher beabsichtigt ist, die Energiefunktion

$$E = -\frac{1}{2} \sum_i \sum_j T_{ij} V_i V_j + \sum_i \frac{1}{R_i} \int_0^{V_i} g_i^{-1}(V) dV - \sum_i V_i$$

zu minimieren, wobei V_i und V_j jeweils Ausgangsspannungen der Verstärker A_i und A_j sind, T_{ij} eine Konduktanz ist, die die verstärkte Eingangsspannung des Verstärkers A_i mit dem Eingang des Verstärkers A_j , der eine Verstärkungsfunktion $g(U_i)$ hat, in Beziehung setzt, R_i der äquivalente Widerstand am Eingang des Verstärkers A_i und g_i^{-1} das Inverse von g_i ist und



gekennzeichnet ist

durch eine Einrichtung zum Ausgleichen der Antwortgeschwindigkeiten der Verstärker, wobei die Einrichtung eine Konduktanz T_{ij} enthält, wobei jede Konduktanz T_{ij} so ist, daß $(T_{ij}^+ + T_{ij})$ eine Konstante ist ($T_{ij}^+ - T_{ij}$) gleich der Konduktanz T_{ij} ist, wobei T_{ij}^+ eine Konduktanz ist, die zwischen dem Ausgang V_i des Verstärkers A_i und dem Eingang des Verstärkers A_j angeschlossen ist und T_{ij} eine Konduktanz ist, die zwischen dem Ausgang $-V_i$ des Verstärkers A_i und dem Eingang des Verstärkers A_j angeschlossen ist.

Revendications

1. Un réseau comprenant un ensemble d'amplificateurs A_i (10) ayant chacun une entrée sur laquelle est développée une tension d'entrée U_i , et chacun d'eux développant une tension de sortie non inversée V_i et une tension de sortie inversée $-V_i$, avec les deux tensions de sortie liées à la tension d'entrée par une fonction en S , g_i , des moyens pour appliquer un courant d'entrée I_i à l'entrée de chacun des amplificateurs A_i , un réseau de conductances pour appliquer les tensions de sortie positives et négatives aux entrées, et comprenant des valeurs de conductance qui sont sélectionnées en fonction de la nature de l'opération de décision pour laquelle on désire minimiser la fonction d'énergie :

$$E = -\frac{1}{2} \sum_{i,j} T_{ij} V_j + \sum_i (1/R_i) \int_0^{V_i} g_i^{-1}(v) dv - \sum_i I_i V_i$$

dans laquelle V_i et V_j sont des tensions de sortie des amplificateurs respectifs A_i et A_j , T_{ij} est une conductance entre la tension d'entrée amplifiée de l'amplificateur A_i , ayant une fonction de gain $g(U_i)$, et l'entrée de l'amplificateur A_j , R_i est la résistance équivalente à l'entrée de l'amplificateur A_i , et g_i^{-1} est l'inverse de g_i , et CARACTERISE PAR des moyens pour égaliser les vitesses de réponses des amplificateurs, ces moyens comprenant un sous-réseau associé à chacun des amplificateurs et connecté entre l'entrée et la sortie négative de chacun des amplificateurs, ce sous-réseau comprenant une interconnexion en parallèle d'une résistance (32) et d'un condensateur (31).

2. Un réseau comprenant un ensemble d'amplificateurs A_i (10) ayant chacun une entrée sur laquelle est développée une tension d'entrée U_i , et chacun d'eux développant une tension de sortie non inversée V_i et une tension de sortie inversée $-V_i$, avec les deux tensions de sortie liées à la tension d'entrée par une fonction en S , g_i , des moyens pour appliquer un courant d'entrée I_i à l'entrée de chacun des amplificateurs A_i , un réseau de conductances pour appliquer les tensions de sortie positives et négatives aux entrées, et comprenant des valeurs de conductance qui sont sélectionnées en fonction de la nature de l'opération de décision pour laquelle on désire minimiser la fonction d'énergie :

$$E = -\frac{1}{2} \sum_{i,j} T_{ij} V_j + \sum_i (1/R_i) \int_0^{V_i} g_i^{-1}(v) dv - \sum_i I_i V_i$$

dans laquelle V_i et V_j sont des tensions de sortie des amplificateurs respectifs A_i et A_j , T_{ij} est une conductance entre la tension d'entrée amplifiée et l'amplificateur A_i , ayant une fonction de gain $g(U_i)$, et l'entrée de l'amplificateur A_j et g_i^{-1} est l'inverse de g_i , et CARACTERISE PAR des moyens pour égaliser les vitesses de réponse des amplificateurs, ces moyens comprenant une conductance T_{ij} avec chaque conductance T_{ij}^+ , de façon que $(T_{ij}^+ + T_{ij})$ soit une constante et que $(T_{ij}^+ - T_{ij})$ soit égale à la conductance T_{ij} , en désignant par T_{ij}^+ une conductance connectée entre la sortie V_i de l'amplificateur A_i et l'entrée de l'amplificateur A_j , et par T_{ij} une conductance qui est connectée entre la sortie $-V_i$ de l'amplificateur A_i et l'entrée de l'amplificateur A_j .