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(54) Title: NEURONAL NETWORK STRUCTURE AND METHOD TO OPERATE A NEURONAL NETWORK STRUCTURE

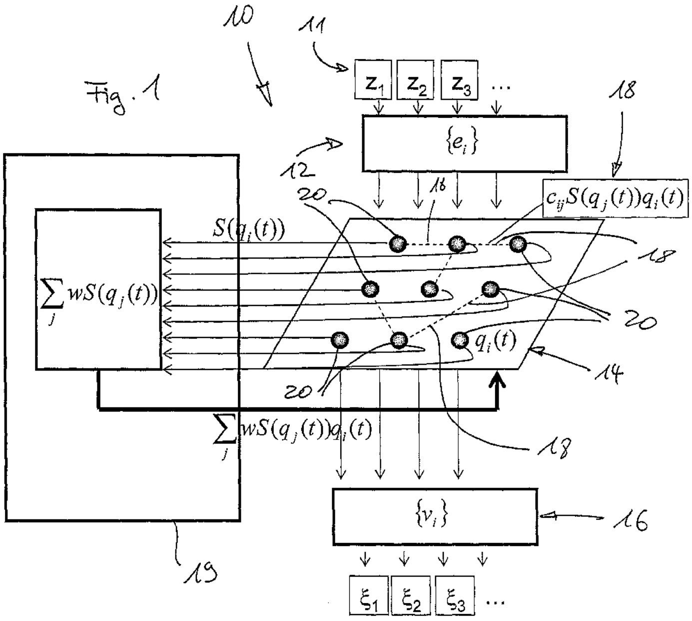


Fig. 1

(57) Abstract: A neuronal network structure comprising a processing unit, an input unit for inputting variables into the processing unit, and an output unit for outputting processed variables from the processing unit, wherein the processing unit comprises a plurality of automata interconnected one with each other by means of identical interconnections forming a connectivity matrix, and wherein the neuronal network structure has a process - based architecture.

Neuronal network structure and method to operate a neuronal network structure

Technical Field

[0001] The present invention relates to a neuronal network structure comprising a plurality of automata interconnected one with each other. The present invention further relates to a method to operate such a neuronal network structure. Particularly, the present invention relates to a network of automata interconnected by synaptic links.

Description of the Related Art

[0002] Computations based on sequentially processing architectures operate upon series of input states and generate an output state. The representation of a continuous process is foreign to such a state-based architecture and very difficult, if not impossible, to realize. To realize such a continuous process, it typically requires the digitization of the continuum into many discrete states to enable the state-based architecture to work with the input. However, most processes in nature are continuous and show lawful behaviour, such as for example the swinging of a golf club, the evolution of traffic flow, the interaction between people, and the process of thought to name just a few. The representation of such lawful and systematic behaviour as a sequence of states is artificial and only imposed by the limiting constraint of the state-based architecture, a prominent example for which is the well-known von Neumann architecture.

[0003] There have been suggestions in the literature to overcome the constraints imposed by von Neumann-type computer architectures by means of neural (or neuronal) computer architectures, also known as neural or neuronal networks or computers.

[0004] Hoppensteadt et al. discloses in "Oscillatory Neural Computers with Dynamic Connectivity" (Phys. Rev. Letters Vol. 82, 14, 2983 to 2986) a neural computer consisting of oscillators having different frequencies and being connected weakly via a common medium forced by an external input. Even though such oscillators are all interconnected homogeneously, the external input imposes a dynamic connectivity, thus creating an oscillatory neural network taking into account rhythmic behaviour of the brain. The approach consists in treating the cortex as network of weakly autonomous oscillators, a selective interaction of which depends on frequencies.

[0005] "When Instability Makes Sense" by Ashwin et al. (Nature, Vol. 436, 36-37) discloses the processing of information in neural systems by means of unstable dynamics wherein the switching between states in a neural computation system is induced by instabilities. The dynamics of the neural system thus explores a sequence of states, generating a specific pattern of a neural activity which for example represents a specific odour.

[0006] EP 0 401 926 B1 discloses a neuronal network structure comprising a plurality of interconnected neurons and means for information propagation among the neurons, wherein the information propagation from transmitting neurons to a receiving neuron is determined by values of synaptic coefficients assigned to neuron interconnections, in which network memory accesses of the synaptic coefficients are avoided and the number of arithmetic operations which would be at least equal to the number of input neurons in each case is reduced.

Summary

[0007] In contrast to the known neural computational architectures which are also inspired by neural sciences, but operate upon states (such as Hopfield or Adaptive Resonance Theory (ART) networks for example), the present invention proposes a neuronal network computational architecture which is based upon processes rather than states and in which a computation is identified with the execution of a process. A process, contrary to a state, is a continuous flow reproduction of a set of time-dependent variables.

[0008] The process-based architecture according to the invention is composed of a network of automata interconnected by synaptic links. The nodes of the network are automata equivalent to neuronal populations and are characterized by their time-continuous activity (firing rate). The dynamics of the network automata is defined by time-continuous dynamic systems (such as integral and/or differential equations) and hence can be implemented by basic electronic elements (such as, for example but not limited to, voltage controlled oscillators, optical oscillators, lasers or oscillators of other kinds). The synaptic links are connections between the automata. A process is determined by the entirety of the temporal behaviours of the network nodes or automata, which may have an arbitrarily large complexity. The process-based architecture of the invention could thus be also described as a cognitive architecture.

[0009] The invention is thus able to handle, process and operate in a process-based manner an N-dimensional system which is defined by means of a set of time-dependent (scalar or vector) variables $q_1(t)$, $q_2(t)$, ..., $q_N(t)$. Each of the (scalar or vector) variables describes the activity of a node. In conjunction, the variables describe the dynamic behaviour of the total network, which itself is a high dimensional system. With the invention, lower dimensional behaviour is insured to arise in the totality of network variables and can be described, controlled and encoded in the high dimensional structure, without making reference to a state-based machine. It is in this sense a process is understood, that is as the emergence of low-dimensional behaviours within a complex network.

[0010] According to the invention, a symmetry breaking in the interconnections between the network's automata allows for weight changes in the respective couplings, thus generating a controlled network behaviour. With other words, the encoding of the lower dimensional process is performed by means of the symmetry breaking of the weights of the couplings. Programming of the neuronal network structure of the invention is thus performed by realising the encoding. This could also be described as a manipulation of the interconnections' symmetries. The invention also allows for a certain redundancy as one given function can be realized by various weight changes, resulting in a higher flexibility of the computing architecture and allowing for robustness against errors or lesions.

[0011] With the mechanism according to the invention, it becomes possible to define a physically existing neuronal network of N dynamic elements and to connect these elements via N^2 directed couplings (or interconnections). Such a neuronal network serves as the central processing unit (CPU) of a process-based architecture according to the invention.

[0012] Thus, the invention devises entirely new computational paradigms. Processes (continuous sequences) will be represented in their natural framework, i.e. they will be computed in a machine working with continuous processes. One of the main advantages of the invention is the simplified treatment and solution of problems which are considered difficult in state-based architectures.

Robustness of function is a further major advantage of the present architecture since function can be represented in various realisations. Speed and ease of programming are additional potential benefits.

[0013] Further features and embodiments will become apparent from the description and the accompanying drawings.

[0014] It will be understood that the features mentioned above and those described hereinafter can be used not only in the combination specified but also in other combinations or on their own, without departing from the scope of the present disclosure.

[0015] Various implementations are schematically illustrated in the drawings by means of an embodiment by way of example and are hereinafter explained in detail with reference to the drawings. It is understood that the description is in no way limiting on the scope of the present disclosure and is merely an illustration of a preferred embodiment.

Brief Description of the Drawings

[0016]

Figure 1 shows a highly schematic depiction of a neuronal network structure with process-based architecture according to the invention.

Figures 2A to 2C show three scenarios of the architecture of Figure 1, illustrating the flexibility of the process-based architecture of the invention.

Figure 3 illustrates the conceptual basis of the process-based architecture of the invention.

Detailed Description

[0017] In the context of the present application, a process is the set of all lawful behaviours which can be captured by a dynamic system, for instance a set of ordinary differential equations. It is to be noted that this is different to the mere execution of one behaviour (identical to one specific time course) for a certain initial condition.

[0018] According to the invention, an m-dimensional process, described by its state variables $\xi \in \Re^m$, arises from a high-dimensional network dynamics, described by its state variables $q \in \Re^N$, with dimension N>>m in a well-controlled fashion. This is achieved with a time-scale separation into a slow and fast dynamics, by means of which time-scale separation the target process arises from the full network dynamics as the slow dynamics establishes after an initial fast transient. It is captured by the so-called phase flow on the manifold (cf. Figure 3), which can be intuitively understood to be the flow in the subspace utilized by the process within a much larger space.

[0019] Figure 1 shows a possible embodiment of a neuronal network structure 10 with process-based architecture according to the invention. The neuronal network structure 10 comprises an input unit 12 which is connected to a processing unit 14. An output unit 16 is connected to the processing unit 14 for outputting the results delivered by processing unit 14. The output unit 16 can also operate as a storage means for storing results, or additional storage means can be provided. The neuronal network structure 10 further comprises a memory 18 for symmetry breaking patterns.

[0020] The processing unit 14 comprises a plurality of automata or nodes 20, depicted by circles (cf. also Figures 2A to 2C). The automata or nodes 20 are interconnected with each other by means of so-called synaptic links (cf. for example Figure 2C), depicted with 18 and 19 in Figure 1. Each node 20 receives the common feedback depicted with 19 as known by the person skilled in the art of neuronal networks. It is to be noted that the terms "automata" and "nodes" are to be understood as equivalents in the context of the present application.

[0021] In the following, the operation of the invention is described, referring to the figures.

[0022] The time scale separation according to the invention is accomplished through the symmetry breaking of the relative connectivity in an identically connected network of the nodes 20. Through adjustment of the symmetry of the weight differences 18, any desired low-dimensional dynamic system can be realized. If no such symmetry breaking takes place, the only coupling is via the mean field feedback 19. The low-dimensionality poses only a small constraint since most "coherent" processes in natural systems are low-dimensional despite the fact that the system per se is high-dimensional. Each node in the network of N nodes 20 shows a time continuous activity described by a (scalar or vector) variable $q_i(t)$ for the i-th node and time t.

[0023] If the connectivity matrix of the network structure 14 is described by $W(q)=(w_{ij}(q))$, then the dynamics of the entire network 14 can be described by

[0024] $$\dot{q}_i(t)=N(q_i(t))q_i(t)+\sum_j w_{ij}(q)S(q_j(t))+I_i(q_i,t) \qquad (1)$$

[0025] where $N(q_i(t))q_i(t)$ denotes the nonlinear intrinsic dynamics of the i-th node and S the nonlinear and adjustable transfer of information between the nodes. The dot indicates time derivative. The time-continuous input $I_i(q_i,t))$ is specific to each node and depends on its activity $q_i(t)$.

[0026] An arbitrary external signal $z_i(t)$ (shown at 11 in Figure 1 as input signal) is spatially encoded in the i-th pattern vector e_i in input unit 12, where $e_i\in\Re^N$. Then these multiple external signals are fed into the network 14 via $\sum_j z_j(t)e_j$ and instantiate the input signal $I_i(q_i,t))=a_i(\sum_j z_j(t)e_j)q_i$ at the i-th node 20. The term a_i

denotes a linear or nonlinear function which is to be adjusted for the appropriate application.

[0027] In the following mathematical model discussion of the network structure of the invention, the input signals are dropped for simplicity of presentation. It is also to be noted that the links 22 between the automata 20 typically depend on the activity of q. This is important to enable the network to produce arbitrary processes as outlined below. For most applications, the multiplicative form of the link, $w_{ij}(q) = w_{ij}\ q_i$ with constant w_{ij}, is sufficient, which will be discussed in the following.

[0028] If all network links have the same constant weight $w_{ij}=w$ and $w_{ij}(q) = w\ q_i$, then it is intuitive that no node can be distinguished from the other and it can be shown that the entire network acts as a single unit. Small weight changes c_{ij} (as indicated by the dashed lines 18 in Figure 1) in $w_{ij} = w + \mu c_{ij}$ introduce symmetry breaking in the above dynamics which can be formulated as follows:

[0029] $$\dot{q}_i(t) = N(q_i(t))q_i(t) + \sum_j wS(q_j(t))q_i(t) + \mu c_{ij} S(q_j(t))q_i(t) \qquad (2)$$

[0030] where μ expresses the fact that the changes are small.

[0031] The first two terms on the right side of equation (2) are the same for all nodes and generate the so-called slow manifold, if certain conditions are satisfied (see below). This manifold is the subspace, in which the i-th process $\xi_i(t)$, where $\xi_i \in \Re^m$, evolves over time. It is related to the full network dynamics by a simple linear projection $q(t) = \sum_{k=1}^{m} v_i^k \xi_i^k(t) + \sum_{j=1}^{N-m} w_j \eta_j(t)$ where q(t) is the vector $q(t) = (q_i(t))$ and v_i^k is the k-th component of the i-th vector storing the i-th slow process $\xi_i(t)$ in the activity distribution. The process $\xi_i(t)$ is comprised of m components $\xi_i^k(t)$. The high-dimensional complementary space is defined by the N-m vectors w_j along with the fast transient dynamics given by $\eta_j(t)$. Since μ is a small parameter, a time scale separation allows discussing the behaviour of the two subsystems independently as follows

[0032]

$$\dot{\xi}_i(t) = N(\xi_i(t))\xi_i(t) + \sum_k wS(\{\xi_i^k(t)\})\xi_i(t) \qquad \text{slow manifold} \tag{3a}$$

$$\dot{\xi}_i(t) = f(\xi_i(t))\xi_i(t) \qquad \text{slow dynamics} \tag{3b}$$

$$\dot{\eta}_i(t) < 0 \text{ and } (N(\xi_i(t)) + \sum_k wS(\{\xi_i^k(t))\}) \le 0 \qquad \text{fast dynamics} \tag{3c}$$

[0033] Here (3a) characterizes the slow manifold. This manifold is attractive if (3c) is satisfied. Note that the brackets {} in (3a) and (3c) denote the appropriate set of variables. If all links 22 are the same, that is μ=0, then the flow on the manifold is zero (cf. also Figure 2C). This is equivalent to the statement that all nodes 20 and connections 22 are identical. If μ

is not zero, then a flow is generated through 18 on the manifold captured by (3b). Since no restrictions are put upon the nature of the symmetry breaking of the connectivity, the dynamics $f(\xi_i(t))$ of the process remains arbitrary and is only determined by the pattern vectors v_i and the intrinsic dynamics of the automata at the network nodes 20. Or in other words, arbitrary flows are generated on the manifold by manipulating the connectivity matrix W. Or one more time in other words, an arbitrary though lawful behaviour is generated on the manifold and defines the process.

[0034] In Figure 2A, the upper eight nodes 20 in the network 14 are disconnected. As a consequence, the lower layer nodes generate a very specific output and map it into the numbered four nodes which serve as the output unit 16. This network is very sensitive to injuries. Particularly, if a lesion occurs, the network function will be destroyed.

[0035] Figure 2C captures a situation in which all nodes 20 are connected by links 22 and somewhat contribute to a similar degree to the outputs 16. This architecture is robust to injuries, but does not allow sufficiently for specificity of the output. In other words, every output will be somewhat similar and no real programming is possible.

[0036] Figure 2B describes the scenario of the invention: all nodes 20 are connected, but symmetry breaking in the connectivity 18 allows for weight changes, thus generating controlled network behaviour as characterized here by $f(\xi_i(t))$.

[0037] Since $f(\xi_i(t))$ and the symmetry breaking of connectivity are not uniquely related to each other, the same function $f(\xi_i(t))$ can be realized by various weight changes. In Figure 2B, two networks are shown hatched at 30 and dotted at 32, respectively, which partially overlap (as shown hatched and dotted at 34). The identical output in output node number 2 can be generated by either the network 30 or the network 32. Such flexibility allows for robustness against errors or lesions.

[0038] Figure 3 shows an evolution over time of initial input conditions. The diagram of Figure 3 has three axes (q_1, q_2, and q_3 for N=3) spanning a space denoted by q_1, q_2, q_3. A planar surface 40 (m=2) defines a manifold spanned by the variables $\xi_i = (\xi_i^1, \xi_i^2)$ of the i-th process. Five initial conditions are plotted and indicated by five respective asterisks. As time evolves, the system's state vector $q(t) = (q_1(t), q_2(t), q_3(t))$ traces out trajectories which move fast to the manifold. Once on the manifold, the dynamics is slower and the trajectories follow a circular flow within the manifold. Hence the emerging process $\xi_i(t))$ approximates the total network dynamics $q(t)$.

[0039] In order to provide a better understanding of the novel process-based architecture of the invention, established notions and terms in state-based computation are compared in the following with the operation of the invention.

[0040] A 'computation' is the execution of a process as prescribed by equation (3b). It is implemented in the network connectivity for μ 0.

[0041] 'Memory' is the ability to recreate the same dynamic process prescribed by the equations (3a) to (3c) and is foremost defined by the symmetry breaking in the connectivity w_{ij}.

[0042] 'Encoding' of processes occurs by breaking the connectivity weights such that equation (3c) holds.

[0043] 'Input' to the network is given as a set of values which will determine the initial conditions for the process to be executed; alternatively, while the process is being executed, these input values can change as a function of time themselves and the process will change accordingly. A metaphor illustrating this could be the following: Two dancers move in a coordinated fashion. One dancer represents the input stream, the other the CPU process. As a function of the first dancer, the second dancer will coordinate his/her dance movements; equivalently, as a function of the behaviour of the input stream, the CPU process will alter its dynamics.

[0044] 'Output' is the read-out of the network and occurs by extracting ξ_i from the network dynamics q, typically by projecting q onto the adjoint coordinate system of v_i

Claims

1. A neuronal network structure (10) comprising a processing unit (14), an input unit (12) for inputting variables (11) into the processing unit (14), and an output unit (16) for outputting processed variables (17) from the processing unit (14), wherein the processing unit (14) comprises a plurality of automata (20) interconnected one with each other by means of identical interconnections (22) forming a connectivity matrix, and wherein the neuronal network structure (10) has a process-based architecture.

2. The neuronal network structure according to claim 1, wherein the interconnections are dependent on state variables.

3. The neuronal network structure according to claim 1 or 2, wherein a process to be processed by the process-based processing unit is defined by a dynamic system such as a set of differential equations.

4. The neuronal network structure according to any one of claims 1 to 3, wherein the processing unit captures a lower dynamics of a given process.

5. The neuronal network structure according to claim 4, wherein the processing unit captures a lower dynamics of a given process by means of a time-scale separation.

6. The neuronal network structure according to any one of claims 1 to 5, wherein a controlled network behaviour in the processing unit is achieved by symmetry breaking of connectivity.

7. The neuronal network structure of claim 6, wherein the processing unit adjusts weight differences of the interconnections in order to obtain symmetry breaking.

8. A method to operate a neuronal network structure a plurality of automata interconnected one with each other by means of identical interconnections forming a connectivity matrix, the operation being process-based.

9. The method according to claim 8, wherein the interconnections are dependent on state variables.

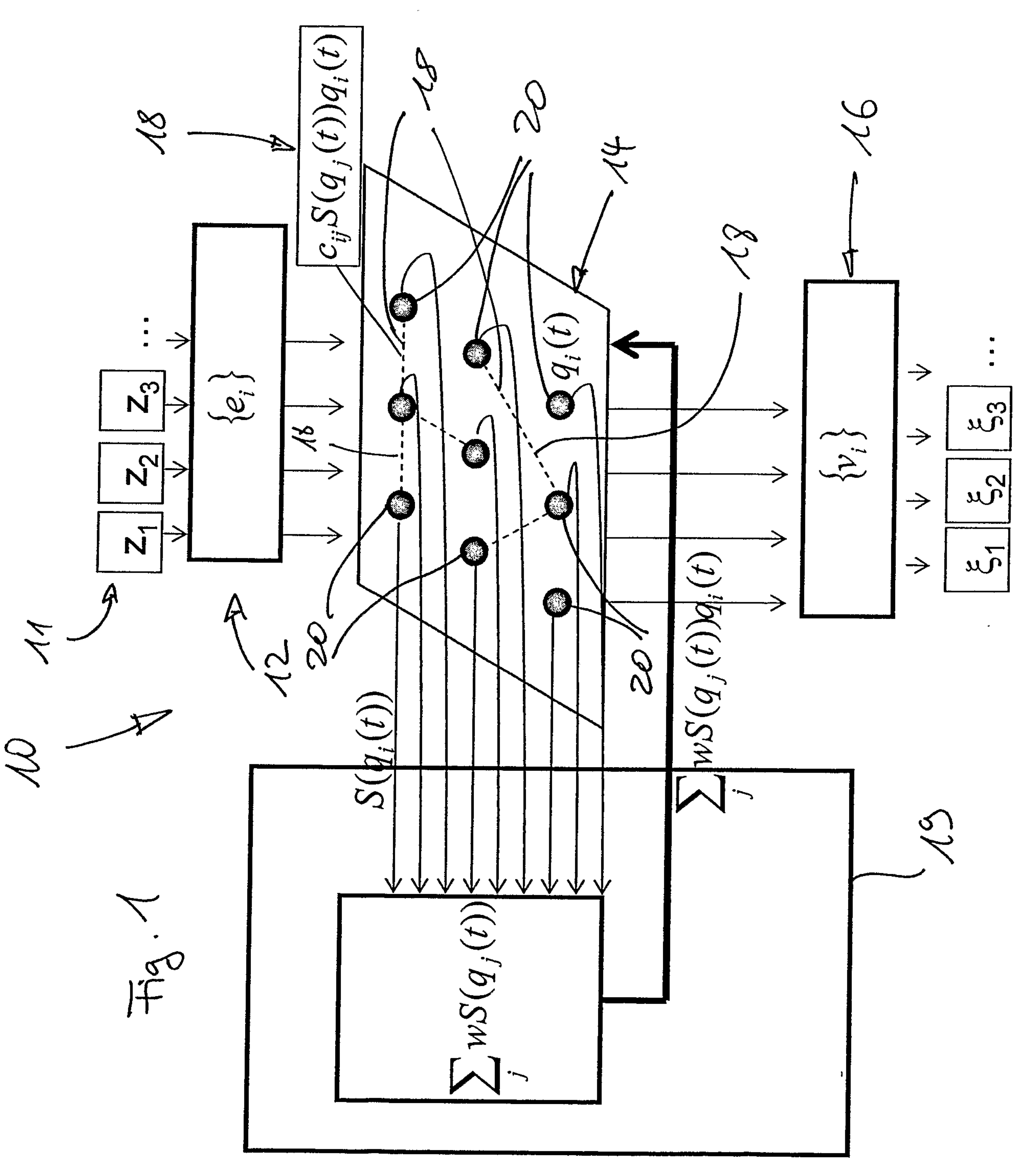
10. The method according to claim 8 or 9, wherein a process to be processed is defined by a dynamic system such as a set of differential equations.

11. The method according to any one of claims 8 to 10, comprising the step of capturing a lower dynamics of a given process.

12. The method according to claim 11, wherein the step of capturing comprises performing a time-scale separation.

13. The method according to any one of claims 8 to 12, comprising the step symmetry breaking of connectivity.

14. The method of claim 13, wherein the step of symmetry breaking comprises adjusting weight differences of the interconnections.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$\sum_j wS(q_j(t))$

Fig. 1

Fig. 2A

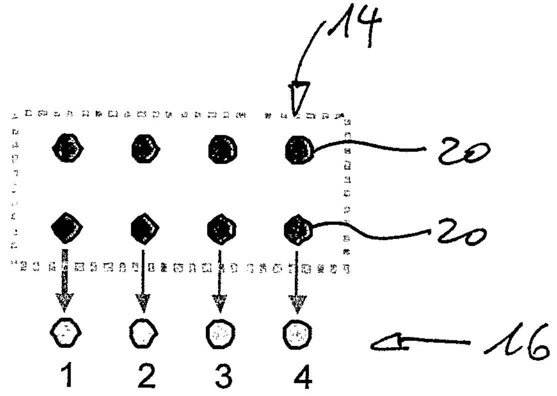


Fig. 2B

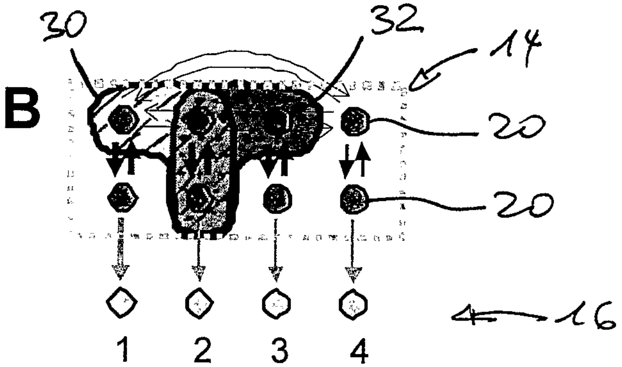
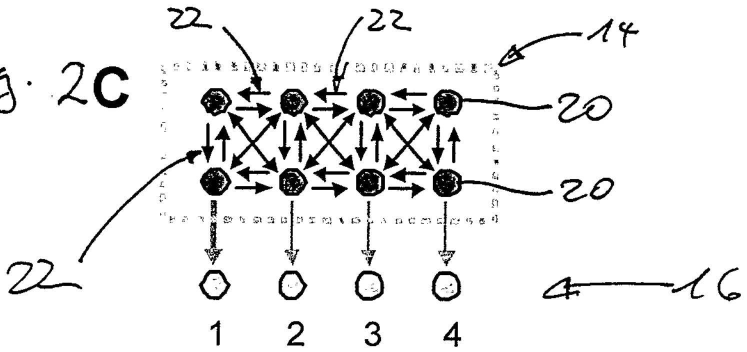


Fig. 2C



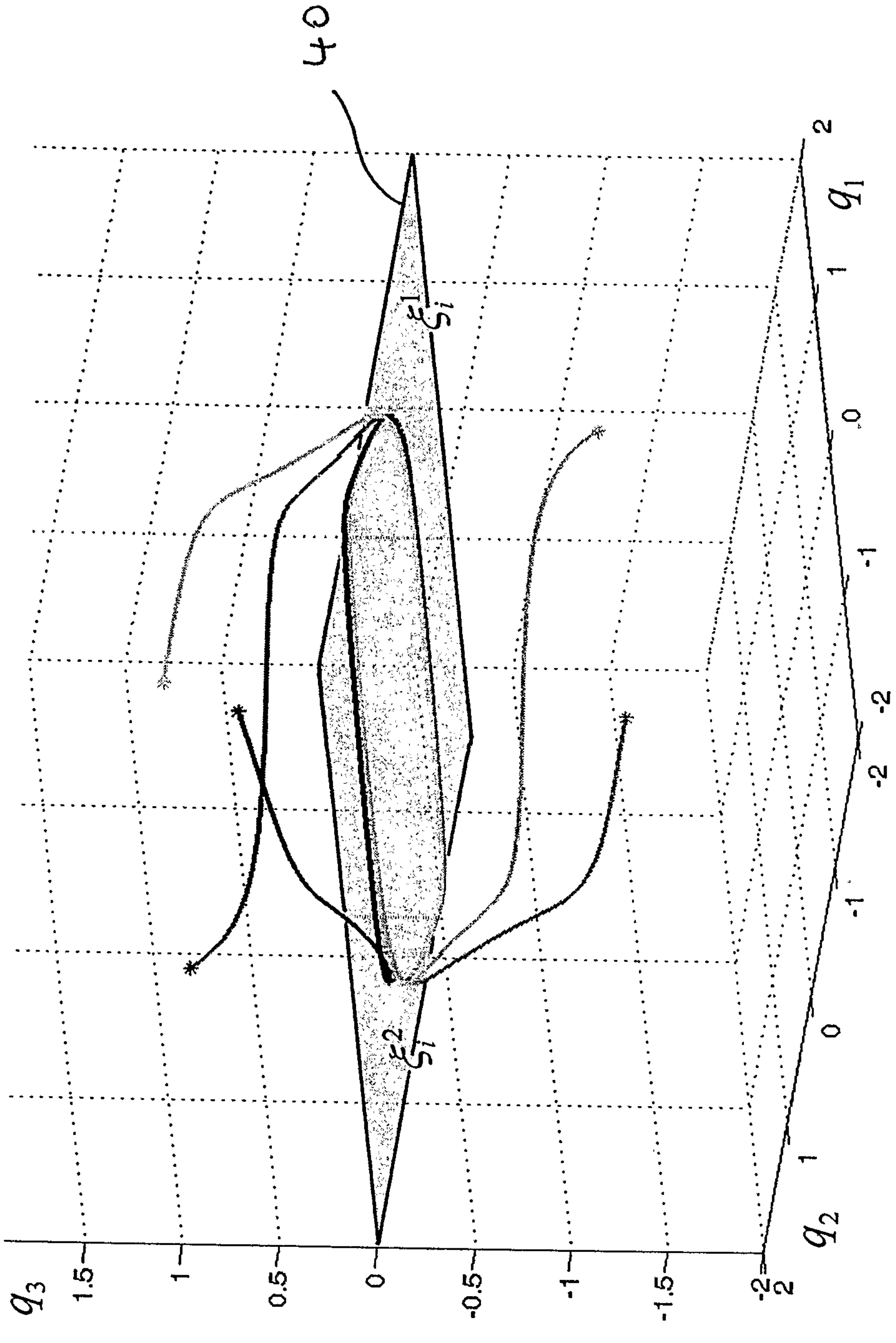


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2007/004176

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06N3/04 G06N7/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, BIOSIS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 5 140 670 A (CHUA LEON O [US] ET AL) 18 August 1992 (1992-08-18) abstract; claims 1-18; figures 1-5 columns 1-13	1-14
X	DE 198 44 364 A1 (GIESE MARTIN [DE]) 30 March 2000 (2000-03-30) abstract; claims 1-3; figure 1 pages 2-3	1-14

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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