Claims

1. A neural network device comprising a neural network for processing the time-series input data (S (t)), comprising

a plurality of n damped electric harmonic oscillators (DHOi, i = 1 to n), $n \geq 8$, the oscillation of each of which follows the general second order differential equation for damped harmonic oscillators of $x_i(t)$: $\ddot{x}_i(t) + 2\beta_i \dot{x}_i(t) + {\omega_{0i}}^2 x_i(t) = 0$ with $b_i = R_i/L_i$ and ${w_{0i}}^2 = 1/L_iC_i$, R_i = resistance, L_i = inductance and C_i = capacity for a corresponding damped electrical RLC harmonic oscillator DHOi, and corresponding b_i and ${w_{0i}}^2$ for other types of damped electrical harmonic oscillators, each of the n damped harmonic oscillators being one cell (nci) of the neural network,

each cell (nci) having an input/output node (IO_i) for receiving a cell input (x_i) such as an electric input of the corresponding damped electrical harmonic oscillator and for outputting the resulting damped harmonic oscillation (h_i),

the input/output node (IO_i) comprising

an input connection (IC_i) adapted to receive any input to the cell and to output the same via a non-linear transfer function as the cell input (x_i), and

an output connection (OC_i) adapted to output the resulting damped harmonic oscillation (h_i), and

a recurrent connection unit (RCU) comprising, for each of the cells (c_i), at least one connection (wi,j) between the input/output node (IO_i) of the corresponding cell (nci) and the input/output node (IO_j) of at least another one of the cells (ncj) for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output node (IO_i) of the corresponding cell (nci) to the input/output node (IO_j) of the another one of the cells (c_j).

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2. Neural network device according to claim 1, wherein

each cell (nci) has an input/output node (IO_i) for inputting the cell input (x_i) as an electric input of the corresponding damped electrical harmonic oscillator via a sigmoid-like transfer function implementing CMOS inverter stage circuit (ICS_i).

3. Neural network device according to claim 1 or 2, wherein

each cell (nci) has an input/output node (IO_i) for receiving all inputs to the cell via an adder (ICA_i) adding all inputs to the cell and outputting the added inputs as input to a saturating non-linear such as sigmoid-like or tanh-like transfer function implementing CMOS inverter stage circuit (ICS_i) outputting the cell input (x_i) as an electric input of the corresponding damped electrical RLC harmonic oscillator.

4. Neural network device according to any one of claims 1 to 3, wherein

the at least one connection (wi,j) between the input/output node (IO_i) of the corresponding cell (nci) and the input/output node (IO_j) of the another one of the cells (ncj) of the recurrent connection unit (RCU) is set to a transmission characteristic $T_{i,j} = w_{i,j} \times h_i$ with $w_{i,j} \in R$ and $|w_{i,j}| \leq 10$, which connection (wi,j) can be, for example, an electric voltage divider or a transmission gate coupling for transmission of the output (h_i) of a corresponding damped electrical RLC harmonic oscillator.

5. Neural network device according to any one of claims 1 to 4, wherein

the at least one connection (wi,j) between the input/output node (IO_i) of the corresponding cell (nci) and the input/output node (IO_j) of the another one of the cells (ncj) of the recurrent connection unit (RCU) is set to a transmission characteristic $T_{i,j}$ and delays the transmission by an output time delay $\partial t_{i,j} = k_{i,j} \times \Delta t$, $k_{i,j} = 0, 1, \ldots, k$, $0 \leq k \leq kmax$, $ti1/10 \leq \Delta t \leq ti1$ and $k_{i,j} \times \Delta t \leq 50\ ti1$, where ti1 is a time series interval of the time-series input data (S (t)) representing either the time interval between subsequent discrete values in case of discrete time-series input data (S (t)) or the time interval between subsequent sampling

values of continuous time-series input data (S (t)), which output time delay can be, for example, an electric inductivity or a clocked output gate for transmission of the output (h_i) of a corresponding damped electrical RLC harmonic oscillator.

6. Neural network device according to any one of claims 1 to 5, wherein

each of the connections (wi,j) of the recurrent connection unit (RCU) is implemented as a (2p+1)-level transmission gate coupling with a first chain of at least 2 serially connected NOT gates coupled to receive the output of the outputting input/output node and a second chain of at least 2 serially connected NOT gates coupled to the other inputting input/output node and a block of 4p transmission gates connected between the outputs of the NOT gates of the first chain and the inputs of the NOT gates of the second chain with $p \leq 10$ such that the transmission weight of the transmission characteristic $T_{i,j} = w_{i,j} \times h_i$ is $w_{i,j} = 0$, if none of the transmission gates is connected to the inputs and outputs of the NOT gates, $w_{i,j} = +w$, if 2w transmission gates are connected phase-correct between the outputs of the NOT gates of the first chain and the inputs of the NOT gates of the second chain, and $w_{i,j} = -w$, if 2w transmission gates are connected phase-shifted between the outputs of the NOT gates of the first chain and the inputs of the NOT gates of the second chain, and

optionally with a transmission output time delay $\partial t_{i,j} = k_{i,j} \times \Delta t$, $k_{i,j} = 0, 1, \ldots, k, 0 \leq k \leq kmax$, $ti1/10 \leq \Delta t \leq ti1$ and $k_{i,j} \times \Delta t \leq 50ti1$, which output time delay is implemented by serially connecting a number l of clocked NOT gates between the output of the outputting input/output node and the other inputting input/output node either behind or in front of the NOT gates of the first and second chains, where the number l of clocked gates is determined as $l = (k_{i,j} \times \Delta t)$ / clock time period, and

optionally with a weight setting block comprising one setting device for each of the a (2p+1)-level transmission gate couplings, which setting device is adapted to close or interrupt a connection via each of the corresponding 4p transmission gates either via permanent closing or interrupting through e.g. melting or etching the corresponding connection lines or not or via programmable closing or interrupting through CMOS transistors switched according to data stored in a SRAM or ROM memory block storing the set weights, and

optionally with a delay setting block comprising one setting device for each of the transmission output time delays $\partial t_{i,j}$, which setting device is adapted to close or interrupt a connection via the corresponding number of l clocked NOT gates either via permanent closing or interrupting through e.g. melting or etching the corresponding connection lines or not or via programmable closing or interrupting through CMOS transistors switched according to data stored in a SRAM or ROM memory block storing the set transmission output time delays $\partial t_{i,j}$.

7. Neural network device according to any preceding claim, wherein

the recurrent connection unit (RCU) comprises for at least one of the cells (c_i) a connection of the input/output node IO_i of the corresponding damped harmonic oscillator DHOi to itself for input and for output, providing self-connectivity, and preferably the recurrent connection unit (RCU) comprises connections for self-connectivity for 5%, more preferably 10%, more preferably 25%, more preferably 50%, more preferably 75%, and more preferably 100% of the cells.

8. Neural network device according to any preceding claim, wherein

a plurality of n1 cells of the n cells with $8 \leq n1$ and with $n1 \leq n$, are arranged in one (first) network layer (L1) and the recurrent connection unit (RCU) comprises, for each of the n1 cells (c_i), at least one connection (wi,j) between the input/output node (IO_i) of the corresponding cell (nci) of the one (first) network layer (L1) and the input/output node (IO_j) of at least another one of the cells (ncj) of the one (first) network layer (L1) for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output node (IO_i) of the corresponding cell (nci) to the input/output node (IO_j) of the another one of the cells (c_j).

9. Neural network device according to any preceding claim, wherein

a plurality of n2 of the n cells with $8 \leq n2$ and preferably $n2 \leq n1$, are arranged in a second (downstream) network layer (L2) and the recurrent connection unit (RCU) comprises, for

each of the n2 cells (c_i), at least one connection ($w_{i,j}$) between the input/output node (IO_i) of the corresponding cell (nci) of the second network layer (L2) and the input/output node (IO_j) of at least another one of the cells (ncj) of the second network layer (L2) for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output node (IO_i) of the corresponding cell (nci) to the input/output node (IO_j) of the another one of the cells (c_j), and

the recurrent connection unit (RCU) comprises

feed forward connections ($w_{i,j}$) between the input/output nodes (IO_i) of the n1 cells (nci) of the one (first) network layer and the input/output nodes (IO_j) of the n2 cells (ncj) of the second network layer for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output nodes of the corresponding cells of the n1 cells (nci) of the one (first) network layer to the input/output nodes (IO_j) of the corresponding cells of the n2 cells (ncj) of the second network layer to establish a minimum potential feed forward connectivity of 10% and a maximum potential feed forward connectivity of 100%, and

feedback connections ($w_{j,i}$) between the input/output nodes (IO_j) of the n2 cells (ncj) of the second network layer and the input/output nodes (IO_i) of the n1 cells (nci) of the one (first) network layer for transmitting the resulting damped harmonic oscillation (h_j) output from the input/output nodes of the corresponding cells of the n2 cells (ncj) of the second network layer to the input/output nodes (IO_i) of the corresponding cells of the n1 cells (nci) of the one (first) network layer to establish a minimum potential feedback connectivity of 10% and a maximum feedback connectivity of 100%, and

optionally a plurality of nr of the n cells with r = 3 or 4 or 5 or 6 and $8 \leq nr$ and preferably $nr \leq n(r-1)$, are arranged in an r-th network layer (Lr) and the recurrent connection unit (RCU) comprises, for each of the nr cells (c_i), at least one connection ($w_{i,j}$) between the input/output node (IO_i) of the corresponding cell (nci) of the r-th network layer (Lr) and the input/output node (IO_j) of at least another one of the cells (ncj) of the r-th network layer (Lr) for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output node (IO_i) of the corresponding cell (nci) to the input/output node (IO_j) of the another one of the cells (c_j), and

the recurrent connection unit (RCU) comprises

feedforward connections (wi,j) between the input/output nodes (IO_i) of the n(r-1) cells (nci) of the (r-1)-th network layer and the input/output nodes (IO_j) of the nr cells (ncj) of the r-th network layer for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output nodes of the corresponding cells (nci) of the n(r-1) cells (nci) of the (r-1)-th network layer to the input/output nodes of the corresponding cells of the nr cells (ncj) of the r-th network layer to establish a minimum potential feed forward connectivity of 10% and a maximum potential feed forward connectivity of 100%, and

feedback connections (wj,i) between the input/output nodes (IO_j) of the nr cells (ncj) of the r-th network layer and the input/output nodes (IO_i) of the n(r-1) cells (nci) of the (r-1)-th network layer for transmitting the resulting damped harmonic oscillation (h_j) output from the input/output nodes of the corresponding cells of the nr cells (ncj) of the (r-1)-th network layer to the input/output nodes (IO_i) of the corresponding cells (nci) of the (r-1)-th network layer to establish a minimum potential feedback connectivity of 10% and a maximum potential feedback connectivity of 100%.

10. Neural network device according to any preceding claim, wherein

the recurrent connection unit (RCU) comprises for the plurality of nr cells arranged in the same r-th network layer, with r = 1, 2, …, 6 and with $8 \leq nr$ and with $nr \leq n$, potential connections (wi,j) for either

all-to-all connectivity of each of the cells to at least 8 and at most 512 of the other cells (ncj) of the nr cells (nci) of the same r-th network layer for transmitting the resulting damped harmonic oscillation (h_i) output from the input/output node of the corresponding cell (nci) to the input/output node of the corresponding other one of the n1 cells (c_j), or

all-to-all connectivity in a King's graph arrangement, or

where the cells are arranged in a ((g1/2 u) x (g1/2 v)) matrix CB, g1= 4, 16, 36, 64, 100, 144, 256 and u, v =2, 3, 4 ,5 ,6, … and (g1 u v) $\leq$ 102400, for first groups (G1) of g1 cells, all-to-all connectivity, wherein these first groups (G1) are arranged in a first chessboard arrangement in a (u x v) matrix CBG1, and for second groups (G2) of g1 cells, all-to-all connectivity, wherein these second groups (G2) are arranged in a second chessboard

arrangement in a (u x v) matrix CBG2 shifted versus the first chessboard arrangement CBG1 by g1/2 cells in both the line and column directions and wherein the second groups (G2) at the edges of the matrix CB in the shift directions are completed by the cells at the edges of the matrix CB at the diagonally opposing positions not covered by the second (shifted) chessboard arrangement CBG2 and the second group (G2) at the corner in the shift directions is completed with the cells in the three corners of the matrix CB not covered by the second (shifted) chessboard arrangement CBG2.

11. Neural network device according to claim 9 or 10, wherein

the recurrent connection unit (RCU) comprises for at least one of the cells (c_i) of the r-th network layer (Lr) layer potential skipping feedback connections (wi,j) to at least one of the cells (c_i) of the (r-s)-th network layer (L(r-s)) with s = 2 or 3 or 4 or 5, and preferably at least 10%, more preferably at least 20% potential layer skipping feedback connectivity.

12. Neural network device according to any preceding claim, wherein

the plurality of n damped harmonic oscillators (DHOi, i = 1 to n) comprise at least two different types of damped harmonic oscillators, wherein each of the at least two different types of damped harmonic oscillator differs in at least the parameter w_{0i} = natural frequency of an undamped oscillation from the other types of damped harmonic oscillators.

13. Neural network device according to any of claims 9 to 12, wherein

the parameters w_{0i} = natural frequency of the undamped oscillations of the damped harmonic oscillators of the nr cells of the r-th network layer with r = 2, 3, ... ,6, are set such that the highest natural frequency of the n(r-1) cells of the (r-1)th network layer is higher than the highest natural frequency of the nr cells of the r-th network layer and the lowest natural frequency of the n(r-1) cells of the (r-1)-th network layer is higher than the lowest natural frequency of the nr cells of the r-th network layer.

14. Neural network device according to any preceding claim, further comprising

an input unit (IU) connected to the input connection (IC_i) of the input/output node of at least one of the cells (nci) and adapted for receiving and inputting time-series input data (S (t)) with a length TI1 to input the input data (S (t)) to input connection (IC_i) of the input/output node of the at least one of the cells (c_i), and

an output unit (OU) connected to the output connection (OC_i) of the input/output node of at least one of the cells (nci) and adapted for outputting output data (O (t)) with an output starting time (OST) set to be a predetermined time interval after the receipt of the start of input of input data (S (t)).

15. A method of training a recurrent neural network device according to any of the preceding claims, comprising the following steps:

a) setting natural frequencies of the plurality of n damped harmonic oscillators (DHOi, i = 1 to n), optionally such that they result in at least three different types of damped harmonic oscillators, wherein each of the at least three different types of damped harmonic oscillator differs in at least the parameter w_{0i} = natural frequency of an undamped oscillation from the other two types of damped harmonic oscillators, and optionally such that, based on a determination of power spectral densities of a plurality of representative samples of time-series input data (S (t)) to be processed and the variance of these power spectral densities, the natural frequencies are distributed over the peaks of this variance with one of the at least three natural frequencies set to correspond to the peak of the variance with the lowest frequency and one of the at least three natural frequencies set to correspond to the peak of the variance with the highest amplitude,

b) setting initial weights $w_{i,j} \in R$ and $|w_{i,j}| \leq 10$ of the connections (wi,j) of the recurrent connection unit, optionally setting initial connection output time delays $\partial t_{i,j}$ of the connections (wi,j) of the recurrent connection unit;

c) conducting a training sequence by processing a plurality of a plurality of representative samples of time-series input data (S (t)) to be processed;

d) evaluating the results of the training sequence of step c) by comparing the same with expected results;

e) performing a Back-Propagation-Through-Time (BPTT) technique based on result of the training sequence of step c) and adapting the weights $w_{i,j}$ of the connections (wi,j) of the recurrent connection unit and optionally the output time delays $\partial t_{i,j}$ of the connections (wi,j) of the recurrent connection unit based on the BPTT result,

f) repeating steps c) to e) until either

f1) step d) result in that the results comply with the expected results or

f2) a preset maximum number of repetitions of steps c) to e) has been reached without reaching step f1), and

g) fixing the weights of recurrent connection unit and optionally of the connection delays according to the weights and connection delays that resulted in the complying results of f1), or ending the training.