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Space–time signal binding in recurrent neural networks with controlled elements

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A B S T R A C T

The possibilities of signal binding in recurrent neural networks with controlled elements are investigated. It is shown that a variety of dynamic space–time structures with new associative properties can be formed in the framework of such networks. A comparative analysis of the properties of linear, spiral single-level and multilevel structures of recurrent neural networks is carried out. Special attention is paid to the possibilities of controlling the associative-spatial interaction of signals in recurrent neural networks. The models of impulse neurons interaction are refined. The results of modeling of associative-spatial signal binding in two-layer recurrent neural networks with different logical structures of the layers are presented.

1. Introduction

Artificial real time recurrent neural networks (RNN) are believed to have a potential of a breakthrough in the domain of cognitive associative processing of large amounts of heterogeneous information. Generalized functions of the above processing in the RNN are the following: binding of processed signals, formation of space–time models of the events under analysis, use of those models for the operative solution of poorly formalized creative tasks. Several types of real time RNN are known. The latter include recurrent multi-layer perceptrons, recurrent Elman networks, real time RNNs, RNNs with controlled synapses, and others [1–3]. Potentially, real time RNNs could be used for solving a wide range of applied problems. However the capabilities of known RNNs do not go far beyond pattern recognition and classification [4–6].

Different signals after conversion to appropriate form can be processed by RNNs. All those signals carrying information about the environment have individual and group spatial, frequency, phase, amplitude, time, structural and other characteristics.

For a full rate cognitive associative processing of these signals advanced RNNs should be more functional than existing ones. They should be able to bind signals and their characteristics at different levels of representation, to switch flexibly from one creative task to another one, to maintain signal processing cycles in the network, to avoid the suppression of the results of signal processing by other input ones, to implement both superficial and deep associative processing.

The ability of RNNs to bind signals at different levels of their representation can provide them more capacious memory as well as faster processing. Successful switching from one task to another one is favorable to the development of more complex cognitive solutions. Maintenance of signal processing cycles in the network, along with other functions, provides a wide range of results content and parameters variation. Protection of the results from suppression by the current input signals can reduce the risks of overloading the RNNs thus significantly increasing the depth of information processing. All those advantages can be achieved if the powers to change space–time structures, directions and types of signals binding depending on the current states of the layers are granted to the RNN.

Second section deals with the works related to the binding problem. In the third section, the variants of RNN structures providing controlled space–time binding of dynamic signals are considered. Section 4 is devoted to models of interaction of controllable elements of such RNNs. The results of the simulation are discussed in Section 5. The final conclusions are given in Section 6.

2. Background

A number of works on the issues of signal binding in the RNNs are known. Among them are publications on the problem of binding and those concerning general approaches to the solution [7–12]. In a number of cases the problem is subdivided into

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several relatively independent ones [10–12]: coordination, unity of perception, binding of variables and visual characteristics, and others. Coordination of the functioning of various neural circuits is often correlated with synchronization. The unity of perception is attributed to the problem of establishing various relationships in the RNNs between color, size, shape, motions and other properties of the observed objects. The problem of binding variables in the RNN is focused on the study of the issues of full rate processing and understanding of different languages. Binding of visual characteristics is one of the more elaborated problems.

There are binding of parts, regions, levels, spatial, temporal, frequency and other characteristics of signals carrying information about objects and processes [8,10,13]. In order to bind the signals in the RNN they are converted to the required form [1,14,15]. Before the signals are put into the RNN they can be decomposed into space–frequency components. In this case, each component can be transformed into a sequence of individual pulses with its frequency and phase being functions of amplitude and phase of the component. Signals can be also reconverted at the output of RNN.

A number of questions on space–time signal binding in RNNs with various hard- and software structures have been studied [1,2,5,13,16–18,44]. To bind the signals in the space different (direct and inverse multi-quadratic, Gauss, Gabor and others) radial functions can be used [1,19–21]. Binding of signals in classical real time RNN [1,2] allows them to be processed quickly, but not in depth. Self-organizing RNNs [22–25] realize deeper processing of information, but they do not meet the requirements of real time. Hierarchical recurrent neural networks [17,26] combine to a certain extent both of those properties. However they are not significantly investigated from the point of view of multilevel binding of signals. The aspects of internal structures at each level and the mechanisms of multi-level transitions are left without due attention.

The papers [16,27] deals with recurrent neural networks providing the possibility of trigger switching of internal connections. In particular, this feature is used when modeling Turing machine [16] by neural networks. However, the potential of the RNN is significantly richer than that of digital machines, which are based on address access to memory. RNNs with controlled synapses are developed. It is known [1] that due to the control of artificial synapses it is possible to change significantly the parameters of signals converging to individual neurons.

In Refs. [3,6,28–33], it was suggested, by means of additional effects on the synapses, to change the parameters of divergent signals and to endow layers of RNN various (linear, spiral and other) logical structures. Also in [6,28,32,33] flexible control of associative interaction of signals is provided. This control is based on a change in the spatial and energy characteristics of signals transmitted from layer to layer depending on the current states of the layers of RNN. Despite the above said the possibilities of controlled signal binding in the RNN still remain unexplored in many respects.

Note that the biological neural network systems are characterized by flexible space–time structures, the manifestation of which is being actively studied now [18,34–36]. Some of the results of those studies can inspire the creation of artificial RNN with a number of mathematical models of the plasticity [1,37,38] and approaches to their hardware implementation [39,40,48] have been developed. The disadvantages of the models include a poor accounting of the conditions of energy distribution along the axon terminals. Those models have not also the possibility of controlling space–time signal binding. The criteria for such control have not been worked out. When binding signals in space and time their energy and phase relationships are not fully taken into account. The implementation of internal homeostatic neuronal plasticity [41,49,50] in artificial RNNs is poorly studied despite the fact that a significant number of studies is devoted to the models of synapses and neurons [1,42,43,45–47]. A comparative characteristic of a number of neuron models can be found in [43]. Those aspects must be taken into account when realizing perspective hierarchical RNNs.

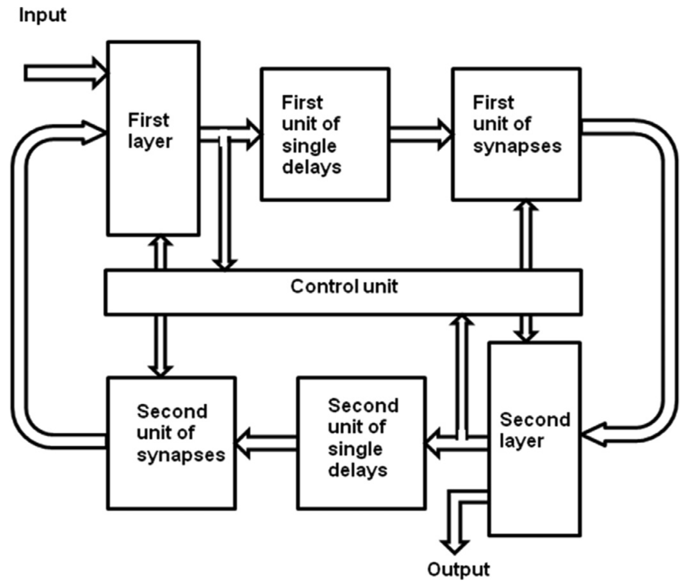

Fig. 1. Scheme of artificial recurrent network (RNN).

Based on the above analysis we can state the following. The issues of changing the space–time structures, directions and types of binding of different signals in the real-time RNN remain largely unexplored. That circumstance hampers significantly the efforts to develop promising ways and means of associative-spatial processing of large amounts of heterogeneous information. It is necessary to search for new solutions that enhance cognitive capabilities of the RNN.

3. Space–time structures of the RNNs with controlled elements

The possibilities of space–time signal binding in the RNN largely depend on the peculiarities of their structures and on the information processing methods that are implemented. Two-layer network with a control unit is considered as a basic one (Fig. 1). The input of this network receives sets of single impulses that carry information about the input signals. In order to form such sets the input signals are decomposed into space–frequency components according to a basis which matches the input layer of the network. Then each component is transformed into a sequence of single pulses with a frequency and a phase as functions of the amplitude and phase of the component. The layers of such a network have the dimension $N = L \times H$, where L is the length and H is the width of the layer. Each neuron in one layer is usually connected to all the neurons of the other layer through the synapses. It is believed that the further the neurons from each other the greater the attenuation in the synapses. The connections between the neurons of the same layer are absent. For the neurons of this network there are three states: expectations, excitations and insusceptibility (refractoriness). Any neuron is excited if the total potential at its input in the waiting state exceeds the excitation threshold.

As a result, the neuron generates a single pulse at the output, and the accumulated charge at its input is sharply absorbed. Excitation is accompanied by refractoriness and the neuron remains in this state more than the delay time of single pulses in the created two-layer contours. One-to-one correspondence between the components of input and output signals in this RNN is provided due to the priority of short connections between neurons.