

# Distributed Machine Learning for Cyber-Physical Systems

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## I. INTRODUCTION

Wireless sensor networks (WSN) are increasingly used for environmental monitoring over extended periods of time. To facilitate deployments in remote areas, sensor nodes are typically small, solar-powered devices with limited computational capabilities. Over the duration of the deployment, harsh weather conditions can lead to problems like mis-calibration or build-up of dust on sensors and solar panels, leading to incorrect readings or shorter duty-cycles and thus less data. Our goal is to automatically learn the normal system behaviour and to use this model to detect anomalies.

In our approach, sensor nodes participate in a distributed recurrent neural network, where each of the sensor nodes hosts a few units and communicates only with its local neighbours. Our online learning is a variant of backpropagation-decorrelation (BPDC) learning [1] with intrinsic plasticity [2] (IP). In a similar setting, we have proposed a distributed fault detection [3] based on echo state learning [4], but the offline learning approach is computationally too demanding to be directly executed on sensor nodes. Our new *Spatially Organised and Distributed Backpropagation-Decorrelation* (SODBPDC) architecture and learning algorithm (Section II) is suited for directly learning on sensor nodes because of a smaller memory footprint than echo state learning during training. In Sect. III, we present results of an application of SODBPDC to fault detection in sensor network data.

## II. APPROACH

WSN spend a large part of their energy on communication between individual nodes. Routing data between distant nodes involves participation of intermediate nodes (“multi-hop”), and thus further increases energy consumption. To distribute a recurrent neural network over a WSN, we let each node host some units of an entire neural network[5]. We restrict connections between units to those hosted on the same node or on nodes in the immediate spatial neighbourhood. This results, on each device, in small local reservoirs with local input units and output units with additional connections between neighbours. From a global perspective, we obtain a spatially organised reservoir, which we train using a distributed version of BPDC learning.

Each sensor node  $q$  hosts the same number  $M_q$  of units, namely  $L_q$  output units,  $N_q$  hidden units, and  $K_q$  input units. The whole recurrent network consists of  $M$  units,

i.e.  $L$  output units,  $N$  hidden units, and  $K$  input units. For first theoretical considerations, it is convenient to represent activations as a global vector  $\mathbf{x}$ :

$$\mathbf{x} = \left( \underbrace{x_1, \dots, x_{L_1}}_{\text{output units 1}}, \dots, \underbrace{x_{L-L_Q}, \dots, x_L}_{\text{output units } Q}, \right. \\ \left. \underbrace{x_{L+1}, \dots, x_{L+N_1}}_{\text{hidden units 1}}, \dots, \underbrace{x_{M-K_Q}, \dots, x_M}_{\text{input units } Q} \right).$$

Likewise, synaptic connection weights between units can be represented in a global  $M \times M$  matrix  $\mathbf{W} = (w_{ij})$ . Activations are updated in a distributed way as in the non-distributed version of BPDC [1]

$$\mathbf{x}(k+1) = \mathbf{W} \mathbf{f}(\mathbf{x}(k)), \text{ with } f_i(x) = \frac{1}{1 + \exp(-a_i x - b_i)}$$

for each time step  $k$ , so that each node computes all local  $x_i(k+1)$ .

### A. Proxy units

In a practical implementation, both  $\mathbf{W}$  and  $\mathbf{x}$  are distributed over multiple sensor nodes. Moreover, there are connections in  $\mathbf{W}$  between units on different devices, which require to have a specified physical location. We store the incoming connections from units hosted on neighbour sensor nodes on the local node. Units with outgoing connections to units on other devices just forward their activations with no changes to the neighbour device. Additional proxy units on the neighbour act as a place holder for remote units and take activations from connected units. From proxy units, there are only local connections to the reservoir or to output units. Proxy units also eliminate the need for all sensor nodes being tightly synchronised, as long as they all use the same interval to process data — typical update frequencies are very low, e.g. once every minute or once every 15 minutes. Newly computed activations are forwarded to connected proxy units where they can be used by the neighbour device. After their values have been used, proxy units are reset to 0 in order to avoid using old values in case of a sensor network link failure.

### B. SODBPDC online learning

Each sensor node is responsible for updating its local output weights. Let  $\mathbf{x}^q$  denote the vector of activations in

$\mathbf{x}$  which can be accessed locally on node  $q$  either directly or by reading out a proxy unit. Let the set  $O$  contain indices  $j$  of output units,  $\hat{O} \subset O$  the local output units, and  $g : O \rightarrow \hat{O}$  a mapping from global to local unit indices. The SODBPDC learning rule is executed on each local sensor node and updates the global matrix  $\mathbf{W}$ :

$$\Delta w_{ij}(k+1) = \frac{\eta f(x_{g(j)}^q(k))}{\sum_s f(x_{g(s)}^q(k))^2 + \epsilon} \gamma_i(k+1),$$

where  $\gamma_i(k+1) =$

$$\sum_{s \in \hat{O}} (w_{is} f'(x_{g(s)}^q(k))) e_{g(s)}(k) - e_{g(i)}(k+1).$$

### C. Training for distributed fault detection

In our application to detect sensor faults, the task is to predict local sensor readings based on information from other nodes. We expect a reading and its prediction to be approximately equal when the sensor works normally. Faults are detected when the difference between the two exceeds a specified threshold. During the initial training period, we assume there are no sensor faults, so that the training output for each sensor is exactly the same as the input time series.

We aim to learn a model of all sensors simultaneously, but independent of the local input. To this end, we create an identical copy of the local recurrent network on each node. The original instance, the primary network, is connected to the local networks on neighbour nodes as described above, and receives normal input from its local sensors. The global network joining all local primary instances with activations  $\mathbf{x}^q$  has an activation  $\mathbf{x}$ . In  $\mathbf{x}$ , all input units are sensor readings at all times. The second instance, the shadow network, has only incoming connections from primary networks on neighbour nodes, but does not forward its local activations  $\hat{\mathbf{x}}^q$  to any other node. Local input units of the shadow network are fed with random noise. This results in an individual global activation  $\mathbf{x}^q$  for each node  $q$ . In each  $\mathbf{x}^q$ , there is no correlation between local input and the local training signal. The primary network is responsible to feed its activations to neighbour nodes. Both the SODBPDC rule and IP

are applied to the shadow network. After application of learning rules, a consolidation step copies output weights and local IP learning parameters from the shadow network back to the primary network.

## III. EXPERIMENTAL RESULTS

*a. Example 1 — comparison to a centralised approach using BPDC and IP learning.* We compared the prediction errors of our approach against an approach using a centralised reservoir of the same size. For both approaches, we simulated link qualities from 10% to 100%. In the distributed approach, this represents the probability of communication between any two nodes, and in a centralised setting the communication probability from any node to central reservoir. The centralised reservoir was used to predict the solar voltage of one node, taking the solar voltage of the remaining 31 nodes as an input. SODBPDC learns slower in the beginning, very likely an effect of the additional random noise signal. For high link qualities, SODBPDC performs equally or better than BPDC, but BPDC manages to maintain lower NRMSE even for poor link qualities.

*b. Example 2 — robustness against multiple failures.* In this experiment we randomly selected an increasing number of sensors to fail, and let faulty sensors return 25% of the original value. We were interested in the prediction error for the remaining healthy nodes, when (a) the faulty sensors continued to feed data into the network, and (b) the input from faulty sensors was replaced with (recursive) predictions. We trained all nodes using the first 43000 values of the time series. Using recursive predictions manages to keep the error very low for up to 29 (out of 32) failed sensors.

## IV. CONCLUSION

SODBPDC is distributed recurrent neural network architecture. It is suitable for fault detection in WSN, where predictions of sensor values are made based on information from neighbour nodes, and it is robust against multiple sensor faults.

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- ternational Conference on Information Processing in Sensor Networks (IPSN 2009)*, pages 373–374. IEEE Computer Society, April 2009.
- [4] Herbert Jaeger. The “echo state” approach to analysing and training recurrent neural networks. GMD Report 148, GMD – German National Research Institute for Computer Science, 2001.
- [5] We use *unit* for components of a neural network, and *node* for devices in a sensor network.