Poster: Approximate Sensing with Vector Symbolic Architectures: The case of fault isolation in distributed automation systems

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ABSTRACT

Due to the stochastic and imprecise nature of sensory data, the current (exact computational) algorithms for their processing introduce unnecessary computational overhead. One of the major trends in the development of computational elements for processing of sensory data is low-power imprecise electronics and accompanying algorithmic solutions for approximate computing. This poster introduces the usage of hyper-dimensional computing and vector-symbolic architectures *in the context of wireless embedded systems*. A problem of fault isolation in a distributed automation system is considered as a showcase. The poster presents the performance of the associative sensing approach as well as challenges associated with the design of communication techniques and network protocols for exchanging of VSA information.

Categories and Subject Descriptors

D.3.3 [**Programming Languages**]: Language Constructs and Features – *abstract data types, polymorphism, control structures*. This is just an example, please use the correct category and subject descriptors for your submission. The ACM Computing Classification Scheme: http://www.acm.org/class/1998/

General Terms

Algorithms.

Keywords

Hyper-dimensional computing, vector symbolic architectures, fault detection and isolation.

1. INTRODUCTION

One of the major scientific challenges with Internet of Things is a transformation of raw data (signals, sensor measurements) into knowledge. This knowledge has an ultimate importance for efficient decision support in cyber-physical systems. The traditional approach to this problem is centralized. Huge amounts of data (Giga- and Terabytes) are normally aggregated in powerful computers where models are built using well-established data mining algorithms. The questions of in-network processing, which were intensively researched in the scope of wireless sensor networks, are so far not given appropriate attention in the IoT context. This is due to very large amounts of data in the first place and a very high computational complexity of the processing algorithms not suitable for low-power and low-performance electronics. On the other hand in-network modeling methods is the necessary prerequisite for increasing the level of intelligence and, therefore, autonomy of IoT-enabled technical systems.

One of the current trends in the development of computational elements are low-power imprecise electronics and accompanying algorithmic solutions for approximate computing [1]. This trend addresses the challenge of stale energy efficiency of the computations, which manifested itself through Dinner index that reached its limit in 2006 [2]. The rationale for imprecise approximate computing is simple. Due to the stochastic and imprecise nature of sensory data, the current (exact computational) algorithms for their processing introduce unnecessary computational overhead.

Hyper-dimensional computing proposed by Pentti Kanerva [3] is a biologically inspired computational framework for pattern processing and similarity-based reasoning. In high-dimensional (HD) computing, all entities are represented by binary random vectors of very high dimension (usually d>>1000). The simple binary arithmetic on such long vectors allows mapping of a well-defined metric for binary similarity (Hamming distance between different HD-vectors) to be a metric of semantic similarity between different concepts represented by these vectors. A mathematical framework called Vector Symbolic Architectures (VSA) further generalizes this mapping. VSA is a bio-inspired framework for representing concepts and their interrelationships for modeling cognitive reasoning using HD data representation. The distinctive property of high-dimensional computing is its extreme robustness to bit errors, which makes it specifically attractive for operation on imprecise hardware [4]. This poster introduces the usage of hyper-dimensional computing and vector-symbolic architectures in the context of wireless embedded systems, discusses performance issues and design challenges.

An IEC 61499 based automation system [5] is considered. This architecture consisting of interacting components (or functional

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blocks), each of which could be characterized by the state of its variables recorded at specific moments in time has been conceived to facilitate the use of distributed automation intelligence. Recent advances in merging the IEC 61499 architecture with multi-agent systems (MAS) [6] show dramatic enhancement of the system's autonomy.

The poster presents a learning system based on the principles of hyper-dimensional computing, which could be implemented on top of an IEC 61499 based automation system. For representing a system-wide state an approach of Holographic Graph Neuron [8] is used. The system-wide state at time t can be therefore be modeled as indices of the recorded at time t *values* (i.e. active elements of each column). Using the VSA approach the system's state at time t is encoded as

$$SYS_t = [\sum_{j=1}^{N} STATE_j^{HD}] \quad (1)$$

where N is the number of system's components and $STATE_j^{HD}$ is the state of component j encoded using high-dimensional binary vector. When a specific system's state leads to a faulty situation, the encoded state is then accordingly labeled. A collection of labeled systems-wide states forms a distributed associative memory, which is used for recalling patterns of system state and predicting faults. A high level overview of the approach is presented in Figure 1.

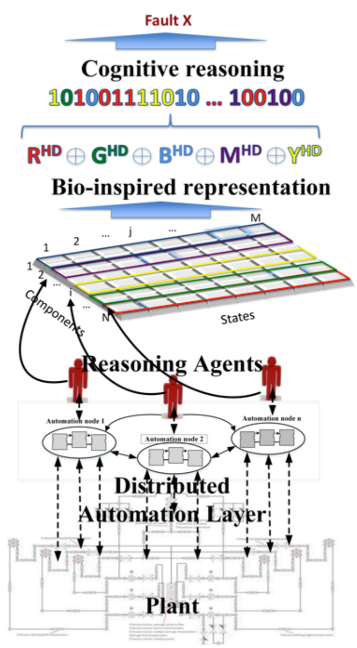

Figure 1. Distributed fault detection system empowered by vector symbolic architectures. Tested for generic nuclear power plant model [7].

The functional failure identification and propagation framework was used to analyze 116 automation components as the sources of hardware faults in the nuclear power plant model [7]. Most of these components were pump and valve actuators. For each type of automation component three failure modes were chosen. For example, a valve actuator can be set to "failed open", "failed closed" or "no electric supply" failure modes which will respectively result in opening, closing or stopping to control the valve. A component–failure mode pair (e.g., "Valve ID_{valve}"–"failed open") in the context of this case study defines a fault, which should be identified during the fault isolation process. Out of 348 possible faults (116 components by 3 failure modes), only 92 faults actually affected the steady-state operation mode of the power plant model. Therefore, these faults can be detected by data-driven fault isolation approaches. In the VSA based system all available features are quantized into 60 levels. All 111 quantized features are then used to represent the system's state as 10 000 dimensional HD vector according to (1). Next, Hamming distances between the formed HD vector and all available fault situations in the knowledge-base are measured. The similarity score for each of 92 faults is the mean Hamming distance for all entries of the fault in the knowledge-base. Finally, the system produces a list of faults sorted in the ascending order according to their similarity scores to the current state of the system.

The results of the use-case study show the accuracy of fault isolation comparable to the classic machine learning methods applied in the same context. The advantage of the hyper-dimensional computing-based solution is in its distributed operation. The distributivity allows the fault isolation subsystem to be an integral part of the distributed automation system of the system. From the practical point, the proposed approach can be used as an additional mechanism on top of the existing fault management system and potentially enables the deployment of such subsystem in standard programmable logic controllers improving the robustness and the decision making for the whole system.

2. REFERENCES

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