HaLOEWEn: A HETEROGENEOUS RECONFIGURABLE SENSOR NODE FOR DISTRIBUTED STRUCTURAL HEALTH MONITORING

Andreas Engel, Björn Liebig and Andreas Koch

Technische Universität Darmstadt
Embedded Systems and Applications Group
Email: {engel,liebig,koch}@esa.cs.tu-darmstadt.de

ABSTRACT

This demonstration shows the usage of a heterogeneous sensor node (HaLOEWEn) for structural health monitoring applications. It employs the Random Decrement technique to aggregate compressed structural health data from a long-term stream of raw sensor data.

Index Terms— wireless sensor network, reconfigurable computing, structural health monitoring

1. INTRODUCTION

Structural Health Monitoring (SHM) helps to reduce maintenance costs of large structures such as bridges or wind turbines by replacing manual inspections with automated damage detection. SHM relies on the acquisition and combination of vibration data collected from acceleration sensors distributed all over the structure [1]. Wireless Sensor Networks (WSN) have been widely adopted for distributed data acquisition [2, 3]. While allowing for a flexible network setup, the wireless transmission of large data streams heavily taxes the limited energy budget of the sensor nodes. Therefore, the SHM computation has to be (partially) distributed to aggregate and filter the sensed data prior to transmission.

The Random Decrement Technique (RDT) is appropriate for a decentralized data aggregation. It estimates the free-decay response of large structures by eliminating random excitations from the measured vibration data. The excitations themselves, caused by external impacts such as wind or traffic on a bridge, are masked by averaging signal windows extracted from the sensor data stream [4]. The remaining displacement response still has to be transmitted through the wireless network to a centralized processing unit for subsequent modal analysis, but RDT significantly reduces the communication volume.

A time-to-frequency-domain transformation in the modal analysis is another way to further reduce the amount of data to be transmitted. If the relevant ranges of the frequency spectrum are known for an application, components outside these ranges can be locally discarded.

To reduce the systems overall energy consumption, the energy cost of the node-local data computation must not exceed the energy saved by the reduced communication rate. Conventional wireless sensor nodes driven by low power micro-controllers (MCU) are not capable of efficiently performing complex computations [5]. As an alternative, we propose a heterogeneous sensor node architecture, utilizing a reconfigurable compute unit (RCU) as energy-efficient hardware accelerator to supplement a conventional radio system-on-chip (RF-SoC) [6]. The HaLOEWEn platform (Hardware Accelerated Low Energy Wireless Embedded Sensor Node) is an implementation of this architecture employing a TI CC2530 RF-SoC and a Microsemi Igloo M1AGL1000 FPGA as its RCU [7].

We demonstrate the benefits of the HaLOEWEn architecture for SHM-applications by efficiently executing the RDT as well as a Fast Fourier Transformation (FFT) to aggregate the sensed data stream as described above. As these two tasks must be executed sequentially, runtime reconfiguration of the hardware accelerator is conceivable but was rejected due to the large amount of energy required to reconfigure the Flash-based FPGA.

2. DEMONSTRATION

Figure 1 depicts the setup of the demonstration. The structure to monitor and its attached acceleration sensors are simulated by an arbitrary waveform generator (AWG), looping a recorded real-world vibration signal (30 s of data, captured at a pedestrian bridge with a person crossing). This use of the AWG simplifies the demonstration setup and allows for reproducible results without relying on unrealistic synthetic signals.

The AWG output is sampled by the analog-to-digital converter (ADC) incorporated in the HaLOEWEn platform and controlled by its RCU. If a certain trigger condition is satisfied, the sampled value is accumulated to the displacement response stored in the SRAM of the HaLOEWEn platform. The trigger checks and accumulations for RDT have been accelerated by the RCU. As multiple triggered signal windows

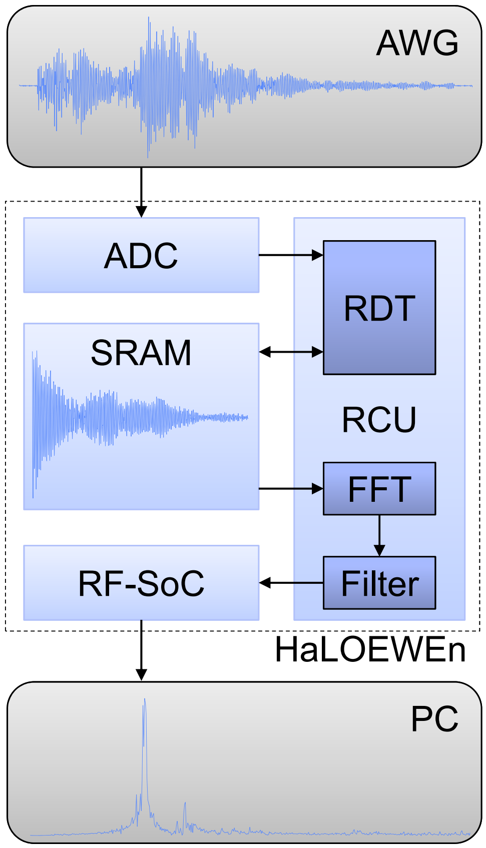

Fig. 1. Demonstration setup: Generation, aggregation and analysis of structural vibration data

may overlap, a single sample may be accumulated to multiple memory locations. This dynamic computational load depends on the characteristics of the input signal and up to 30 accumulations have to be performed in a single sampling cycle for the demonstrated bridge scenario. Due to the hardware acceleration of RDT, the average power drawn by the HaLOEWEn does not exceed $500\ \mu W$ even under highest load conditions. The load-dependent power consumption is as low as $1.6\ \mu W$ per accumulation. A comparative MSP430-based reference implementation requires $22.4\ \mu W$ per accumulation and thus scales significantly worse with increasing load.

After a sufficient number of accumulations, the random parts of the input signal are averaged out and the free-decay response is fed into a hardware accelerated FFT. The HaLOEWEn architecture requires about $500\ \mu J$ to perform a 2048 point FFT. Only the relevant parts of the resulting frequency spectrum are then forwarded to the RF-SoC to be transmitted for the final centralized analysis. To simplify the demonstration, the received spectrum is just displayed. Due to the energy efficient realization of the frequency transformation, only $1\ \%$ of the spectral information has to be discarded to reduce the overall energy consumption.

3. CONCLUSION

This demonstration shows the applicability of the proposed heterogeneous hardware architecture to energy constrained WSN scenarios. The HaLOEWEn platform is especially suitable if more complex computations can be performed in a distributed fashion.

The single-node setup of the demonstration abstracts away the complexity of multi-hop communication and in-network time synchronization. Future work will therefore focus on the hardware acceleration of the network-layer specific functionality.

4. PARTNERS

The demonstrated sensor node was developed in collaboration with the Microelectronic Systems Group (TU Darmstadt). Its application to the fields of Structural Health Monitoring was supported by the Fraunhofer Institute for Structural Durability and System Reliability (Darmstadt). Both collaborations are part of the LOEWE program funded by the Hessian Ministry of Higher Education, Research and Arts.

5. REFERENCES

[1] S. N. Pakzad, G. L. Fenves, et al., "Design and implementation of scalable wireless sensor network for structural monitoring," *Journal of Infrastructure Systems*, vol. 14, pp. 89–101, 2008.

[2] S. Kim, S. Pakzad, et al., "Wireless sensor networks for structural health monitoring," in *Proceedings of the 4th international conference on Embedded networked sensor systems*, 2006, pp. 427–428.

[3] R. Bischoff, J. Meyer, and G. Feltrin, "Wireless sensor network platforms," *Encyclopedia of Structural Health Monitoring*, 2009.

[4] J. Asmussen, *Modal Analysis Based on the Random Decrement Technique*, Aalborg University. Department of Mechanical Engineering, 1997.

[5] A. T. Zimmerman, M. Shiraishi, et al., "Automated modal parameter estimation by parallel processing within wireless monitoring systems," *Journal of Infrastructure Systems*, vol. 14, pp. 102–113, 2008.

[6] A. Engel, B. Liebig, and A. Koch, "Feasibility analysis of reconfigurable computing in low-power wireless sensor applications," in *Reconfigurable Computing: Architectures, Tools and Applications*, pp. 261–268. 2011.

[7] F. Philipp, F. Samman, and M. Glesner, "Design of an autonomous platform for distributed sensing-actuating systems," in *Rapid System Prototyping (RSP), 2011 22nd IEEE International Symposium on*, pp. 85 –90.