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Dynamically Reconfigurable Integrated Sensor Electronics for Magnetic Localisation of Distributed Autonomous Sensor Nodes

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Abstract: The increasing number and variety of sensory principles and embodiments impose growing demands on the versatility and capability of sensor electronics. In particular, mobile and wireless applications based on integrated sensory systems, e.g., from agriculture, automation, smart environments, internet of things, or cyber-physical-systems, aggravate the requirements imposed on sensor electronics, e.g., requesting for reduced uncertainty and higher dependability in the application system realization. The paper will survey and discuss relevant lines in sensor electronics realization, e.g., eigen- or self-x capabilities, with a focus on integration options, both monolithic and packaging based. As an application example for the use of current and development of future sensor electronics, a propriatory location context extension of data logging systems with magnetic localization and synchronization features will be employed as a research vehicle. Current results and a roadmap for the inclusion and benchmarking of novel sensor electronics concepts will be presented.

Key words: Reconfigurable sensor electronics, self-x systems, spiking sensor electronics, wireless sensing, magnetic localisation.

Introduction

From established application fields and markets in measurement, instrumentation, control, and automation sensors and associated sensor electronics, for instance as components in the soaring field of embedded systems, have advanced to a plethora of new application domains. Concurrently, the number of novel sensor principles, technologies, and implementations sees an amazing growth, which imposes more stringent demand on the versatility and capability of sensor electronics.

In particular, mobile and wireless tasks based on integrated sensory systems, e.g., from agriculture, automation, smart environments (SE), ambient intelligence/assisted living (AmI/AAL), body area networks with medical background, internet of things (IoT), cyber-physical-systems (CPS), request for low-power consumption, low uncertainty in measurement, high dependability etc. at low cost. Following the vision of *Smart-Dust* from Berkeley, size and integration and pervasiveness issues, inobtrusively integrating application devices, such as spoons [3], floors etc., with the sensing systems. An important field is data logging in industrial processes, e.g., in chemical, biological, or food related industrial production. Interesting state-of-the-art examples are the FhG IZM e-Grain [1] or the integrated data logger swarm from FZ Rossendorf [2], which was conceived for monitoring of distributed common process parameters, such as temperature and pressure complemented by location context from acceleration and (announced) magnetic sensors.

Electronics for sensory signal conditioning are a relatively small, but indispensable component in systems named above. Signal integrity and measurement uncertainty depend on the quality and properties of sensor electronics realization. Chosen implementation/integration technology has a strong influence on the achievable properties. The following section will survey and discuss relevant research and industrial activities in the light of underlying application and implementation challenges and constraints. The third section will describe the current localization system research vehicle [4] and the fourth section, before concluding, will present results and improvement potential.

Sensor Electronics

Sensor signal conditioning electronics (SSCE) have to interface to various sensory principles and embodiments, e.g., providing environmental information as change of L, C, R, Q, I, U or Z (Impedance spectroscopy) proportional to temperature, humidity, pressure, force/weight, acceleration, magnetic field etc. Further, sensors with regard to the need of external energy for read-out can be bifurcated into active or passive ones. This variety and potential variations in span, sensitivity, selectivity, and stability, impose stringent versatility and flexibility requirements on corresponding sensor electronics. For wired, macroscopic systems, the HBM QuantumX system [5], e.g., MX840A, provides an intriguing, highly generic system solution. For integrated sensory systems, subject to numerous additional constraints, numerous quite singular solutions can be found.

The following discussion will focus on issues of current and emerging solutions for integrated sensory systems. The SIA ITRS roadmap structures ongoing development in integrated systems in two major directions, the *More-Moore* (MM), and the *More-than-Moore* (MtM) direction. The first one relates to monolithic solutions in leading edge technologies for, e.g., systems-on-chip (SoC), while the second one focuses on advance by packaging/MEMS technologies, including 3D approaches, for systems-in-package (SiP).

The MtM allows more cost-effective solutions by integrating off-the-shelf components and dedicated solutions of heterogeneous technologies. Also, aggressively scaled devices of MM technologies are commonly less favorable in the properties required for analog SSCE. Continuing the discussion for MtM and with a focus on mobile and wireless applications, e.g., for wireless-sensor-networks (WSN), the following properties or *desiderata,* driving our research at ISE, can be formulated:

1. Low-Power operations, e.g, reconfiguable low currents and/or *sleep mode* (Power-down, duty-cycling)
2. Control of sensor supply and behavior, i.e., for wheatstone bridges, voltage or current supply with sleep-mode
3. Programmable adaptation of signal and ADC with regard to offset and span for optimum quantization [9, 10].
4. Reconfigurable with regard to offset, gain, topology, power/speed (Eigen- or Self-calibration,-trimming)
5. Extension to dynamic reconfigurablity of the previous parameters based on context sensors, e.g., temperature.
6. Self-monitoring for faults/defects of sensors and electronics, e.g., employing artificial immune systems approach, and self-repair/-healing concepts based on redundancy and dynamic reconfiguration.
7. Inclusion of (micro) actuators in closed-loop sensor operation for the properties of item 6. as well as range extension.
8. Noise reduced design *(SOI vs. Bulk),* noise filtering, and programmable AAF
9. Generic sensor interface, e.g., for C, R, Q, I, U, etc. with low supply sensitivity, low-voltage operation capability, and wide sampling range
10. Multi-channel implementation for synchronous sampling of data of same age
11. ADC included with self-x features (I2C), optional μC with correction algorithms

These properties, which are summarized in Fig.1, have been selectively, but so far, not comprehensively approached by numerous research and commercial implementations.

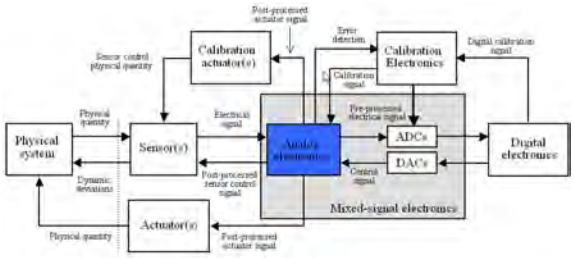

Fig. 1. Conceptual diagram of self-x mixed-signal SSCE with reconfiguration and actuation resources.

For mobile and wireless systems, the seamless integration of sensor, SSCE, and microcontrollers's sleep modes is essential for overall system performance. In [4], a tentative SSCE implementation survey has been given, which will be continued in the following. The AD 8555, AD 8231 or TI PGA 308/309 provide limited reconfiguration [4], e.g., of (temperature compensated) offset and gain, while more advanced solutions, e.g., ZMD 21013 or AD 8290 provide bridge control and sleep modes and even on chip ADC for up to three channels in the case of the ZMD 21013. More recently, ZMDi developed a whole family of bridge sensor conditioning chips with PGA-frontend, various ADC resolutions and on-chip calibration microcontroller, e.g., ZSSC3131 or ZMD31150 [8]. Semtech Corp. offers the ZoomingADC concept embodied by chips as the SX8724 [9, 10], which offer a 3-channel bridge input, PGA and onboard ADC with digitally reconfigurable offset and gain, as well as reconfigurable speed/power properties. A more recent and more comprehensive solution is the Smartec B.V. universal-transducer-interface (UTI) [11], which supports capacitive and resistive elements, including bridges, to be conditioned, uses AC excitation, provides continuous auto-calibration of offset an gain, on-chip ADC as well as power down- or sleep-mode. Micro analog systems [15] introduced MAS6502/03 for resistive and MAS6510 for capacitive sensors. Recent acam Pcap01AK-101xx offers CDC and RDC capability with a RISC CPU on-chip, while the acam Pso9FM1034 offers Time-Digital-Conversion (TDC) for R-bridges [16], which has interesting correspondence with the recent research work depicted in Fig. 2.

Integrated field-programmable-analog-arrays (FPAA) offer a richer functionality, than the so far described solutions. They predominantly allow reconfiguration on a higher level of granularity, i.e., composing heterogeneous SSC and processing/filtering by combining and sizing/configuring analog building blocks. Arrays from Anadigmvortex or Cypress PSOC can be named here [6]. The latter have even seen extension to power electronics (PowerPSOC), however, numerous desirable features of the previous collections cannot be found in today's analog arrays. Concepts of evolvable hardware and related chip implementation (field-programmable-analog-arrays, FPTA) [6] provide reconfigurability on a more fine-grained level and basically allow fault-tolerance and self-x capabilities, but at prohibitively high cost.

Additionally, the control of sensor actuation, e.g., electrostatic force, heating, flip, compensation etc. for self-x capability and/or range extension is predominantly not included in state-of-the-art designs. An increased sensor spectrum and measurement principles, e.g., *impedance spectroscopy* (IS), impose further needs and inspiration.

In current PhD research at ISE by R. Freier, a increasingly generic SSCE in CMOS bulk technology is developed with a focus on *anisotropic-magneto-resistive* (AMR) sensors. Generic as well as reconfigurable or repairable circuits and systems depend on appropriate switching devices. Basic building blocks, e.g., scalable resistors, capacitors, or transistors [6], can be digitally configured by CMOS switches or transmission gates. However, these are non-ideal with regard to inherent parasitics and effective on-resistance. For the latter reason, as well as actuator switching (item 7.), potentially large switches have to be realized, which conflicts cost constraints and dynamic performance. Higher supplies, e.g., by employing charge pumps, for higher gate control voltages as well as the use of high-voltage technology extension (HV-CMOS) transistors switches have been studied with only moderate improvement. Currently, MEMS-based DC-switches or relais emerge, and offer an interesting perspective for analog reconfigur-tion and numerous issues of the item list given above. Progress on this research will be reported in an accompanying paper [14].

In the *MM* direction SSCE can be realized as cells on SoC, or chips for SiP. This implies signal integrity problems due to low and decreasing voltage and noise/crosstalk, e.g., via the substrate, of (extensive) digital resour-ces. One possible approach is to change the paradigm of information representation from amplitude to time [16] or better spiking representation (Spiking SSCE, S3CE) an an implementation style inspired by neuromorphic, adaptive sensor and circuit implementations including the AD-conversion step (see Fig. 2).

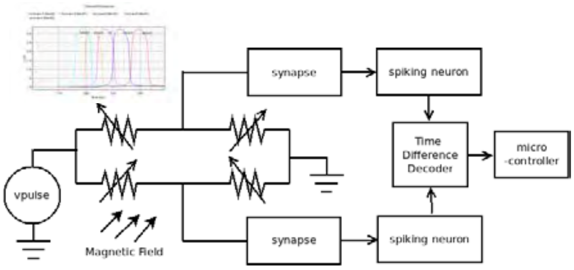

Fig. 2. Tentative concept of S3CE for AMR.

Magnetic Localization System

Distributed and autonomous sensing, e.g., for industrial data logging [1, 13, 4] or indoor-localisation in smart environments requires efficient localization technology and electronics embodiment. At ISE, a magnetic localization and synchronization system for sensor swarm has been developed in a previous BMBF funded mst-avs project [13, 4], that serves a research vehicle to develop and explore new SCCE concepts as outlined in the previous section. Several realizations of 3D-AMR sensors based on commercial chips with voltage and current bridge supply have been conceived and are currently under test in an laboratory set-up for in-situ assessment in the localisation application. One solution, based on the Sensitec AFF755B and AD 8290 chips has been realized on PCB level and additionally, employing AMR sensor (untested) dies and AD 8290 packaged chips recently became available as a prototype version in a dedicated MEMS realization. In Fig. 3., the block diagram of the current sensor electronics of the 3D-AMR, conceived in 2009/2010, is depicted. The sensor is connected to the AD 8290 instrumentation amplifier, which provides gain 50, no offset control, current control of the bridge, and power-down of bridge and amplifier by the microcontroller (atmel XMEGA256A3).

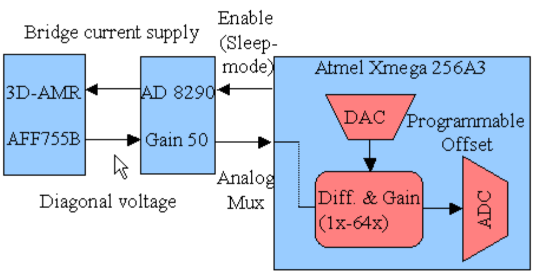

Fig. 3. Block diagram of 3D-AMR SSCE for magnetic localization and synchronization with first self-x features.

The AMR sensor actually provides offset compensation by the possibility of flipping the sensitive layer, measuring before and after flip, and calculating the difference. In the developed prototype of the wireless sensing and localization system, the stimulating coils provide in two successive steps a magnetic field in two opposite directions, reducing the need for flip operation to sensor saturation avoidance [4]. However, as the offset at the output of the AD 8290 can be large and gain 50 will not allow to use the full quantization range of the ADC, the zooming concept [10] was adopted, by employing ADC differential mode, and determining in a self-calibration cycle channel specific offset for x,y, and z-channels.

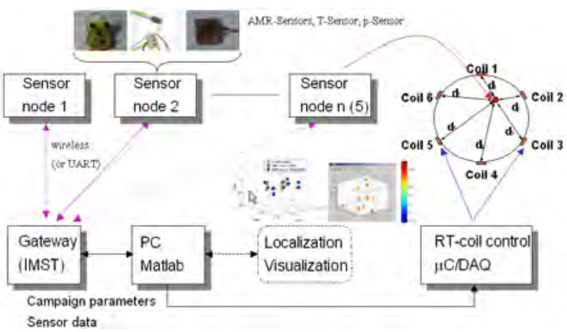

Fig. 4. Block diagram of the ROSIG-demonstrator of a wireless sensor swarm with magnetic localization and synchronization for industrial data logging.

This will be subtracted from the AD 8290 output and the gain will be set to achieve close as possible full scale exploitation of the ADC. Reading positive and negative coil stimulation with the sensor and subtracting the digital values will eliminate residual offset due to drifting.

Fig. 5. PCB-development version of wireless sensor node with wireless (IMST), T (UST),p, and 3D AMR sensing in the demonstrator volume.

The *proof-of-principle* localization system reported in, e.g., [4, 13] has been extended to a front-to-back demonstrator with real-time coil control, magnetic localization and first-cut synchronization, temperature and pressure measurement capability, wireless data transfer, localization algorithms, and sophisticated process data visualization. The major differences to earlier project work [4, 13] is the completed PCB-level sensor node (see Fig.4.) with limited ADC 12 bit capabilities compared to previously employed DAQ-board.The concept depicted in Fig. 3. helped to make up for the deficiencies of the final target platform. Additionally, alternative 3D-AMR nodes with current and voltage mode set-ups, with different power-management/ sleep-mode, and zooming properties have been developed and compared.

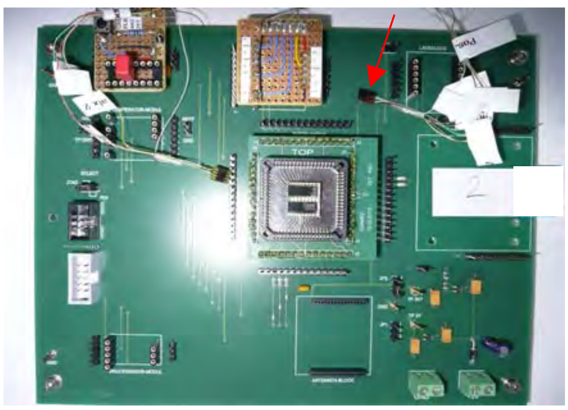

Fig. 6. Wireless sensor node base PCB partially equipped with RMPD 3D-CSP modules layouted & produced by microTEC based on the discrete versions.

Currently, alternative 3D integration options, e.g., MID, LTCC, 3D-printing, active-multi-layer (AML) [17], and RMPD 3D-CSP of the former project partner microTEC for the 3D-AMR sensor and the overall sensor node are compared. Fig. 6. shows the sensor node development system partially equipped with MEMS counter parts of the discrete ones in Fig. 5., in particular a 3D-AMR (top right).

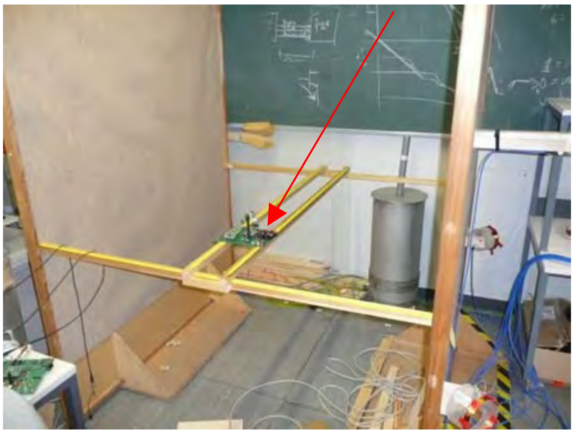

Fig. 7. Demonstrator volume for WSN with six coils placed in a tank-like cylinder-arrangement.

Though a completely integrated MEMS sensor node is aspired for applications, e.g., in brewery industry, the PCB development version is of value, as it is possible to test and benchmark novel sensor electronics applications. Fig. 7 shows one sensor node in the current laboratory demonstrator set-up, which has been described in [4]. It should be mentioned, that the concept has been validated with various volumina of increasing size, e.g., in the Warsteiner brewery (see Fig.7).

Fig. 8. Demonstrator localization with 12 coils placed on a brewery tank of Warsteiner in 2011.

The coil control has been improved with regard to [4] by employing a real-time pattern generator, that will be synchronized with the sensor nodes by the magnetic field. Fig. 9. shows the ROSIG-demonstrator GUI with the current localization algorithm, which is multi-lateration, but more advanced techniques providing better results have been by now developed and employed.

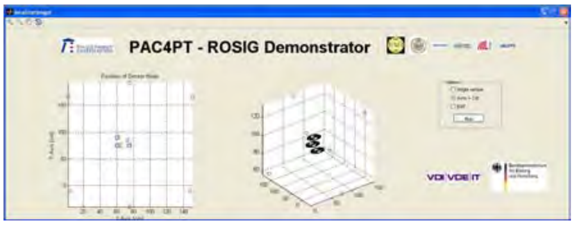

Fig. 9. ROSIG-demonstrator GUI with localization and measurement data results visualization.

Further, dedicated measurement results visualization for swarm data visualization and analysis have been conceived and implemented.

Current Demonstrator Results

In this section, results with the demonstrator based on the AMR755B and AD 8290 SSCE (see Fig. 3.) will be presented. The demonstrator simulates a measurement campaign in an industrial environment. The Matlab backend in Fig. 9. connects via a gate-way of IMST to the wireless nodes and configures them, including campaign length and measurement interval. The nodes synchronize their clocks to the magnetic field of the pattern generator given in Fig. 4.

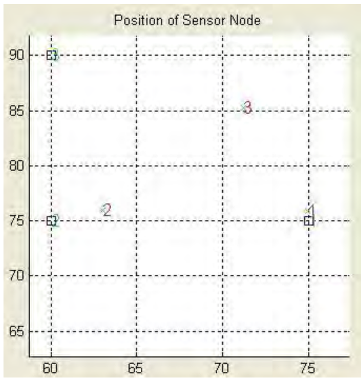

Fig. 10. Simulated campaign length three with actual (cross) and sensed location (box) in x,y plane.

The sensors iterate between 8.5s (@3.7V, 8mA) long measurement (T, p, location context) and sleep mode state. After the campaign and sensor retrieval, they are read-out via the gate-way and the data gets processed, i.e. compu-ting x,y,z-coordinates of the location in Fig. 10.

One option for results visualization is shown for one node and campaign length 3, where a palette is shown at the location each measurement in which the diameter of the disc, T (red disc) , p (blue disc), is proportional to the determined span of the measurand. More information, e.g., time and/or conductivity, IS data, or humidity can easily be added. Localization accuracy or mean error (location, tank scale, and coil size dependant in the order of ~10cm) can be employed as bench-mark for assessing different SSCE solutions. Currently, two remaining main error sources can be identi-

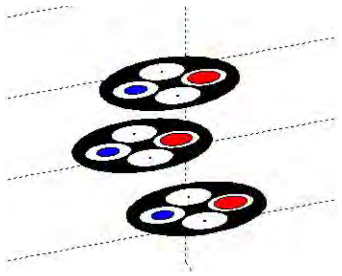

Fig. 11. Result visualization of location context and T (red disc) , p (blue disc) measurement.

fied. Random contributions due to noise in sensor and SSCE chain as well as background fluctuations due to other field emitting devices. Deterministic contributions due to demonstrator scaling and currently employed computational models. Fig. 12 shows an error map in one x,y-

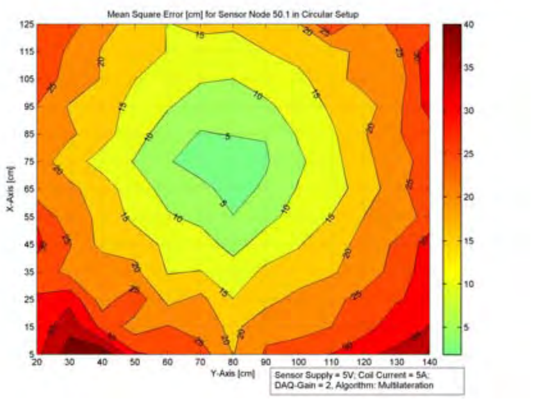

Fig. 12. ROSIG-demonstrator example error map.

plane, clearly outlining the increase of error from the center to the fringes, which demands for algorithmic compensation.

Conclusions

The paper surveyed the state of and trends in SSCE with a focus on the application in a mobile, wireless measurement system for an industrial data logger with magnetic localization and synchronization. Inspired by this task, generic and self-x SSCE concepts are pursued, e.g., based on MEMS switches or spiking concepts, for the research vehicle, which is currently optimized with regard to error reduction, scaling to different scenarios, including smart environment applications, e.g., AmI/AAL, Smart-Home [3] etc., a mobile demonstrator, and sensor node 3D-integration.

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