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Robust & Technology Agnostic Integrated Implementation of Future Sensory Electronics based on Spiking Information Processing for Industry 4.0

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Abstract : The ongoing advance in integrated electronics and sensors technology jointly with recent application challenges, e.g., from automotive, home automation to Industry 4.0, imposes stringent requirements on sensor conditioning and conversion electronics with regard to diversity, genericness, accuracy, and robustness hard to be met by traditional amplitude coding. Moving from amplitude to time domain is a valid alternative. In our work, we pursue a spike-coded approach based on peripheral neural assemblies. Bio-inspiration, e.g., Tropotaxis based methods, the Jeffress' model of sound localization and snake prey detection using its tongue are employed in a spiking architecture to avoid the sensitive scaling networks of the common approaches. Two corresponding architectures have been evolved, designed, and the first one has been advanced to the manufacturing of a first 350 nm CMOS chip, amenable, e.g., for XMR sensors, with variable bit resolution. First test results in a prototype system show principle expected functionality, but also the need for continuous inherent adaptation, which will be pursued in future work in the next generation of robust spiking sensor electronics chip. The second approach has been simulated as a proof of principle design creating a 16 bit ADC with a sampling rate of 50 kHz, with a design which can be rapidly scaled improving all its parameters.

Key words: Bio-Inspired Electronics, Self-X Signal Conditioning, Neural ADCs, Adaptive Spiking Electronics, Neuromorphic computing

Introduction

Robust multi-sensing systems are rapidly gaining momentum for the design of intelligent systems in numerous domains, e.g., from automotive to home and industry automation. The most recent incentive comes from the Industry 4.0 initiative, that demands both for more versatile and accurate yet affordable and robust multi-sensory systems. The corresponding requirements, occasionally summarized as Sensors 4.0, impose stringent demands on the design of integrated sensor electronics, trying to move costly calibration, surveillance, and maintenance of integrated sensory systems to inherent, batch-manufacturable performance monitoring and restoration, which was originally denoted as Eigen-X or Self-X capabilities. In [2] the ongoing development of sensor electronics both with regard to achieving generic as well as Self-X-sensor electronics has been summarized. The focus has been on the classical amplitude coded information processing, which is increasingly vulnerable to the problems of shrinking of devices in More-Moore microelectronics, e.g., due to drastically reducing supply voltages and signal swings as well as mismatch and reliability problems. An interesting alternative for sensor and measurement systems is provided by moving from the amplitude in the time domain, as can be seen by, e.g., CMOS-integrated Time-Domain-Converters (TDC), that convert sensory value representations into proportional time intervals, which are accurately converted into digital value representation. Already in [2], the first results of another alternative approach to robust and technology agnostic sensor signal conditioning and conversion have been introduced. In this paper, the general information processing concept and the results of the first chip implementation will be presented. Inspired by neural information processing and hardware realization, a spike coding of sensory information has been employed on various levels. In the first step, sensor to spike (S2S) conversion takes place, including the aspects of conventional sensor signal conditioning and delivering a differential output, where the sensory information is encoded as the time difference of a spike pair. In the second step, the spike pair serves as input to a spike to digital conversion unit (SDC), that generates a digital output according to the Jeffress' model, where the bit resolution can be increased by sequential evaluation of neural codes in the network. Currently, the first design and circuit bases on the leaky-integrate-and fire neuron (LIF) and corresponding coincidence detectors , but alternative realizations based on digital primitives and also the alternative concept of Tropotaxis are possible and pursued

After general introduction to the sensor signal processing concept, the design, implementation, and first test results of our 350 nm CMOS proof-of-principle SSDC chip will pre presented and an outlook on robust, adaptive integrated sensor electronics for future Sensor 4.0 systems as baseline for Industry 4.0 will be given.

Survey of Alternate Signal Conditioning & Conversion Methods

The most exploited approach in moving towards alternative signal conversion techniques has been the TDCs which convert the pulse width to digital value using flip-flops and delay chains. The simple TDC structures are delay line approaches shown in Fig 1., where the resolution of the TDC depends on the smallest delay structure on the delay line [3]. In [3] the author also describes Vernier based TDC structures where small mismatches in delays of start and stop signals can lead to higher resolutions. Another approach describes TDCs where the buffers chain is looped and a counter is used to count the number of times the loop is used. These approaches are interesting as they unintentionally relate to natural approaches.

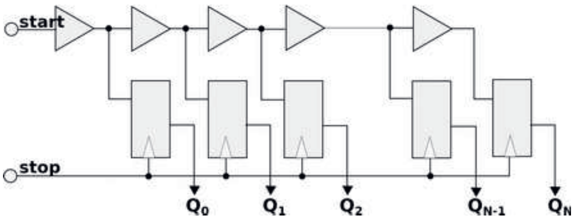

Fig 1: A delay line based TDC structure

Another set of approaches that have always been developing have been the neural approaches beginning from Hopfield's work [4] in 1986. However, this and the derived works have been in amplitude domain. Over the turn of the century, many authors have moved to more biological spike-time domain for ADC design. A low power Bio-Inspired ADC [5] , ADC based on time interval maps [6], and other interesting Spiking concepts [7],[8],[9]. In [9] authors have created a spiking ADC which works based on the mismatches due to manufacturing. This configurable ADC based on NEF neurons is interesting, however, each chip has to be individually calibrated which is not practical for large volume manufacturing.

The other alternative approaches relate to concepts which are inspired from biological sensors. There is a lot of research [10], [11] where the sensors inspired directly from nature are presented. In this work we present a work motivated, not from sensors but from signal conditioning techniques found in nature.

Bio-Inspired Signal Conditioning

Competitive evolution of predator and prey with respect to each other can be seen everywhere in nature from chemical generation (e.g., Capsaicin) in plants, poison/venom generation in prey and predators etc. The most interesting evolutionary track for us are the improved sensors and sensor information processing techniques from natural selection and evolution. Among these the predator-prey relationships seem to improve the sensing based on localization of the each other. This type of localization is broadly described using the term "Taxis" which generally refers to a movement of organism towards or away from sensory stimuli.

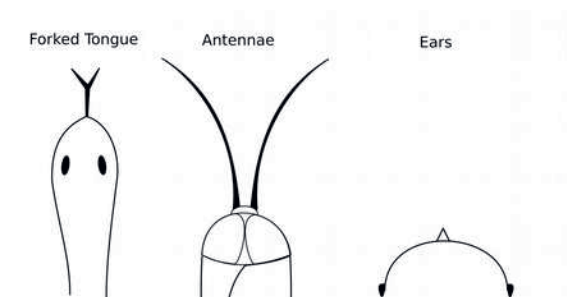

Fig 2: Convergent evolution of symmetry in predator-prey localization

Interestingly similar sensor information processing concepts have evolved in different species independently in a "convergent evolution" as shown in Fig. 2. The forked tongue of the snake, antennae of insects, ears in mammals have evolved with different sensors, but with similar information processing techniques in peripheral neurons. This is called "Tropotaxis" where a symmetrical set of sensors are used to detect the location of the sensory stimulus.

The other type is "Klinotaxis" where a single set of sensors are used to detect the sensory stimulus by re-sampling over time. Interestingly ADC techniques similar to "Klinotaxis" can be seen in successive approximation converters, in spike domain converters like [5], slope converters and closed loop TDCs, where the ADC simulates movement towards the signal while correcting itself appropriately.

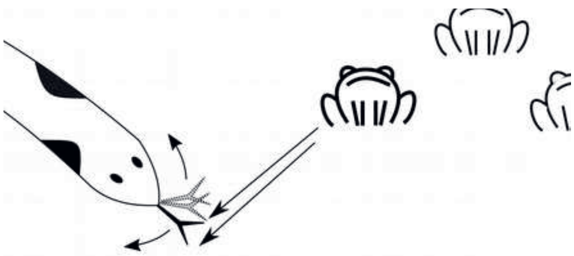

Fig 3: Tropotaxis towards prey using forked tongue of snakes

Tropotaxis shown in Fig. 3. where, the snake is moving towards its prey by moving its tongue to locate its position is has several advantages over Klinotaxis based techniques. Cockroaches seem to move from Tropotaxis based methods to Klinotaxis based methods when one of the antennae is cut off [13]. In our work, we have two designs based on tropotaxis. The first one is based on Jeffress' model of sound localization in human ears, where we move with the assumption that the head position is stationary.

The second approach is based on snake head/tongue movement where the snake moves towards its prey. The prey position is abstracted into the spike time distance values by making use of Wheatstone bridge and Sensor to Spike Converter units as the transduction elements. In the absence of a Wheatstone full bridge based sensor, the concepts can make use of fixed reference, behaving similar to Klinotaxis based techniques. We can observe from here that Klinotaxis based techniques need an external reference while the Tropotaxis based techniques are self referential.

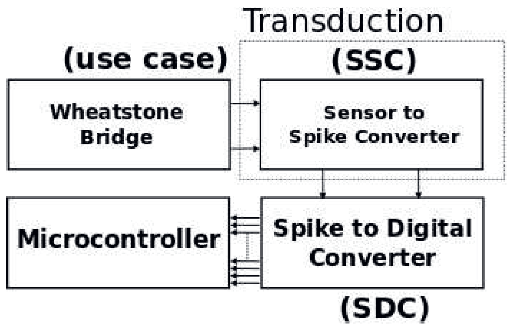

Fig 4: Block diagram of the bio-inspired concept

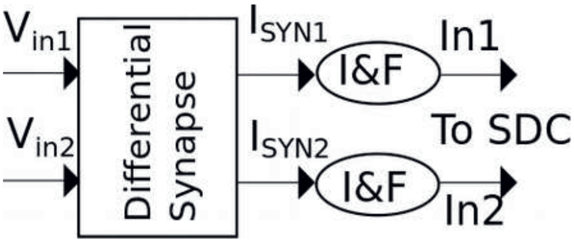

Fig 5: SSC Sensor to Spike Convertor

CMOS Implementations of our Bio-Inspired Concept

In both the concepts we have worked on, we require signals from two or more sensory elements. This can be provided by a Wheatstone full bridge. The transduction of the differential voltage to differential time signal is done using the sensor to spike converter described in [14] and shown in Fig. 4. [14] also describes the first SDC design shown in Fig. 5. This follows the concept of auditory localization to localize the analog signal. The incoming pulses/spikes are delayed in the delay line and the corresponding coincidence detector activates providing a 1 of n coding. The coincidence detector is also able to provide spikes time which are proportional to the distance between pulses in a short span. This time can be used to create a place coding as described in [15].

The chip designed using this technique is shown in Fig. 7. The chip was designed with AMR sensor AFF755B [16]. The chip has a conversion time of 6 µs which leads to a speed of 330 kHz. It is capable of 8 bit accuracy in the basic mode (1 of n coding) and this can be extended to 12 bits or more using place coding. This proof of principle design works with 3.3V vdd & is designed with 350 nm technology. Since the components work with pseudo digital pulses, the voltage scaling will not affect the concept. The use of delay chains have a technology limit which can be overcome by moving to smaller technologies.

This design (Fig. 6.) seems to have similarities with the delay line TDC concept (Fig. 1). However, there are some important differences. The TDCs use pulse width modulation, where there cannot be a “zero” detection and they move only in a single direction. Here the pulse can be in any order or position. This is similar to the difference between Klinotaxis and Tropotaxis, where the latter is naturally selected by evolution.

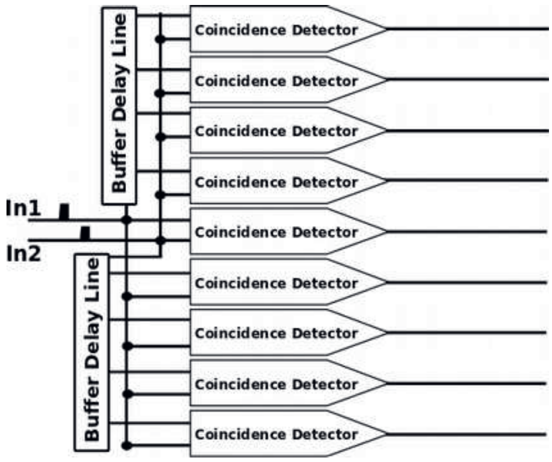

Fig 6: SDC design

The new design (SDC2) for SDC presented in this work is based on snake head/tongue movement towards the prey. Here the tongue movement is simulated by a delay loop as shown in the Fig. 8. The loop starts when the first pulse arrives and ends at the arrival of the second pulse. An asynchronous counter counts the number of times the pulse moves throught the loop. The circuit is direction independent with a time based winner take all circuit selecting the path of the first arriving pulse. When one of the output flip flops activates, the counter is stopped. This has some advantages and disadvantages to the previous design. This design occupies a much smaller area, however, consumes much more power (316 mW) compared to the SSDC (10 mW) in 350 nm ams technology. This is due to the presence of the asynchronous counter in the design. This can be reduced by designing a more low power asynchronous counter or by technology scaling.

This design shows similarities to single slope converter. However, it must be noted that this uses digital concepts and pulse time encoding exclusively. It is also robust as it is bidirectional and has a zero detection capability.

There are several advantages of these symmetrical structures over traditional approaches. The problems due to variations during manufacturing can be checked and corrected by swapping of the inputs in a second measurement. The inputs can be swapped at

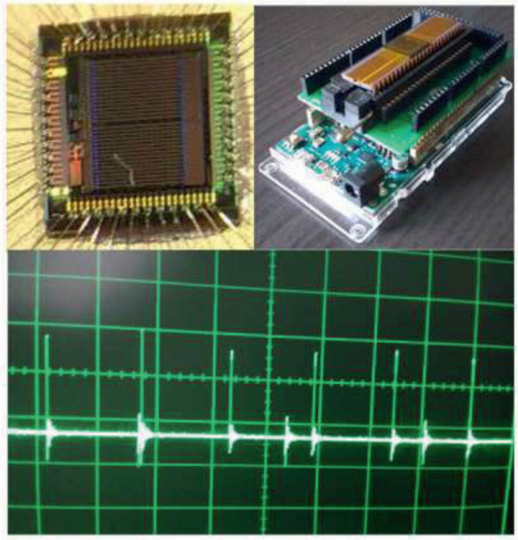

Fig 7: SSDC chip, prototype shield, spike outputs from SSC

different parts of the flow before the SDC. By simple swapping variations due to manufacturing in delays, malfunctioning detector elements etc can be corrected to a large extent. Another observation is that these techniques move away from the sensitive scaling networks towards robust self-referential approaches.

In the first cut design of SDC2 we use a delay of 16ns which is much higher than the limit of the technology. This leads to an LSB of 16 ns. With a counter of 16 bits and appropriate sensitivity of the SSC this can work as a 16 bit converter. So the increase in area is minimal compared to the increase in resolution.

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The goal of these designs is to place them as part of an SOC. The circuits except for the SSC part are mostly digital and work with pulses. These will not be affected by digital noise. and the circuit can be designed safely to be a part of any SOC.

The two approaches differ in power and area as described earlier. However, the main difference lies in the design time line. The second approach will be able to compete with simple improvements in design, immediately with commercially available ADC chips. However, in the long run, the first approach with adaptive elements and using more biological population based (redundant) approach will be able to produce robust results while providing low power capabilities. The approaches will only improve with technology scaling unlike their traditional counterparts. These naturally inspired approaches are also technology agnostic as they depend on neural modules which have been designed in digital, analog and optical technologies.

Experiments and Results

The design SDC2 was simulated with values from -5500ns to 5500 ns, where negative sign indicates pulse 2 appearing before pulse 1. Since this was a nominal simulation the results in both directions were identical. They can be seen in Table 1.

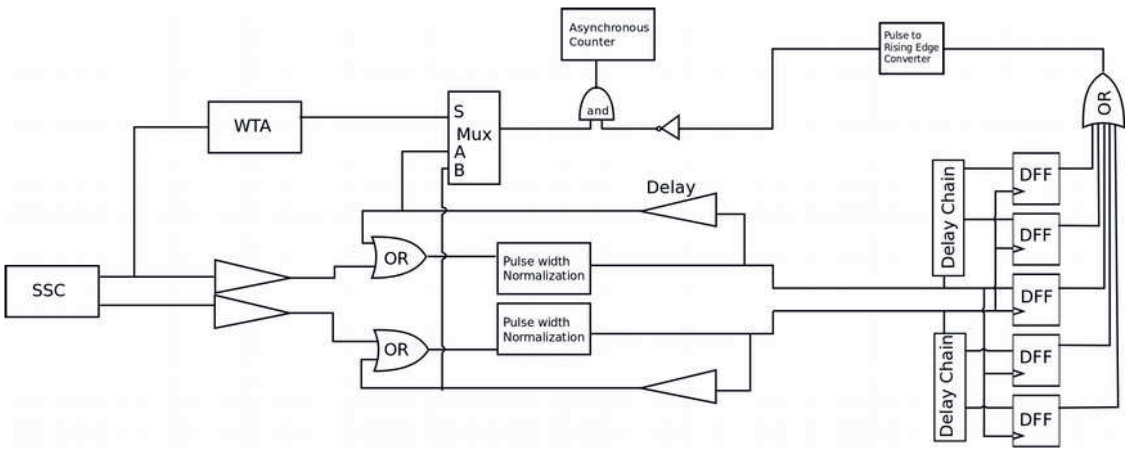

Fig 8: Tropotaxis Based SDC circuit. Implemented on Cadence schematic level in 350nm CMOS.

From these experiments, we can see that the offset error can be compensated by the center coincidence detector/flipflop. The max INL of the first cut design with pre-designed components is 6 LSB and the DNL is 2 LSB. These can be reduced by making use of custom components and better stop control.

Pulse Distance (ns)	Ideal Value X [* LSB ns]	Obtained Value X [* LSB ns]
0	0	0
500	32	31
1000	64	63
1500	96	94
2000	128	126
2500	160	156
3000	192	188
3500	224	220
4000	256	251
4500	288	283
5000	320	314
5500	352	346

Table 1: SDC2 results (LSB = 16 ns)

The second set of experiments deal with the prototype testing of the SSDC shield. The spike outputs from the SSC can be seen in Fig. 7. The SDC has been separately tested using pulse distance inputs generated by an FPGA board. Two outputs from the results are shown in the Fig 9.

Conclusion

The progress in integrated electronics technology as given in the ITRS roadmap and the recent application challenges, e.g., by Industry 4.0 imposes stringent requirements on sensor conditioning and conversion electronics hard to be met by traditional amplitude coding. Moving to the time domain is a valid alternative. In our work, we pursue bio-inspired concepts based on peripheral neural assemblies. In this self-funded work, a first proof-of-principle chip, denoted as SSDC, has been realized and tentatively tested, showing principle expected functionality In the next steps of the work, complete testing and the design and implementation of an adaptive system will be pursued in parallel with design manufacturing and testing of the second design approach. The self referential principle, reconfigurability and future adaptation and redundancy will lead to a new generation of Self-X sensory systems [12] for, e.g.,, Industry 4.0

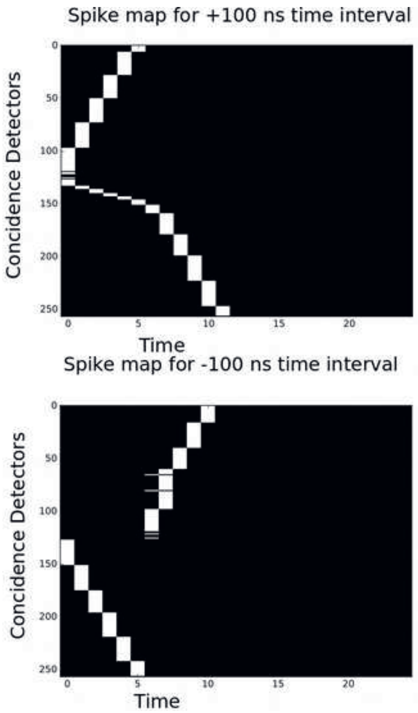

Fig 9: Spike maps of outputs from SSDC chip (SDC). (-ve indicates swapped order)

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