Programmable Mixed Signal Front-End for Sensor Applications

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***Abstract*—This work presents main approaches to developing a programmable mixed-signal front-end for sensor electronics based on signal transimpedance amplification and integration. In accordance to Internet of Things concept requirements a Programmable System on Chip PSoC 5LP is used for mixed-signal front-end implementation. In comparison to the basic transimpedance amplification and integration circuits, the output voltage of new solution is modulated over the whole voltage range of the power supply. As a result, the enhanced resolution and accuracy of further analog-to-digital conversion are obtained. Simulation and experimental results of parameters investigations have been presented.**

Keywords—mixed signal front-end, sensors, embedded system, system on chip, programmable integrator.

I. INTRODUCTION

Up-to-date stage information technologies and sensor electronics within the concept of the Internet of Things (IoT) sets increasingly high requirements for hardware, software, and firmware tools of sensor electronics. Miniaturization, the capability of stable operation at low-voltage power sources, the possibility of being reconfigured programmatically and multifunctionality become crucial parameters of signal chains in modern sensors [1].

A new concept emerged in sensor electronics, mixed-signal front-end along with its component, analog front-end [2]. The paper addresses problems of developing signal converters within the data fusion concept recently emerged in information technologies [3]. In general, data fusion means combining multiple data sources to obtain more accurate, consistent, and valuable information than any individual data source can provide [4]. Data fusion techniques are typically used in prognostics systems [5], smart ubiquitous environments including IoT [6], navigation systems [7], image processing systems, particularly medical imaging [8], human-machine interface devices and diagnostics devices including brain-computer interface [9], etc.

In sensor engineering, the data fusion concept gave rise to sensor data fusion or, for brevity, sensor fusion. This term mainly refers to heterogeneous sensor data fusion, i.e. fusion of data from integrated heterogeneous sensors. The latter are information sources that exploit different measurement techniques [10]. Among the main research topics in this area, one should mention multisensor data fusion algorithms [11], analysis of judicious fusion of inconsistent data obtained from integrated sensors [12], algorithms and unified framework for integrated sensors [13], etc. Some sample modern data fusion solutions include but are not limited to navigation systems [14], human activity monitoring [15], allergens detection and study [16].

II. TASK AND OBJECTIVES

The objective of this work is to develop a programmable mixed-signal front-end for sensor electronics based on transimpedance amplifier (TIA) and mixed-signal integrator (MSI) [17] and study its characteristics within data fusion problems. Problems of developing such signal converters are presented particularly in [18] and [19]. High efficiency of TIA is typical of primary transducers in current-output sensors like photodiodes, phototransistors, magnetotransistors, inductive sensors, and a wide range of impedance spectroscopy transducers. An example of using TIA and MSI in intelligent sensing is discussed in [20], whereas [21] considers their application in bioelectronics devices. Such signal converters are used in wireless power transfer (WPT) technology and near field communications (NFC) [22]. Design of electronic devices based on TIA and MSI is presented by humidity sensors [23], sensors for pH monitoring [24], glucose sensors [25], etc.

For further development of the subject of the mentioned publications, in this paper we solve the problem of developing an embedded system for data fusion applications whose novelty consists in an expanded dynamic measurement range and enhanced measurement accuracy based on transimpedance amplification and programmed integration. Such combination solves the problem of designing multifunctional signal conversion systems including those for numerous optical, electromagnetic or impedance sensors within the data fusion concept. Taking into account the above-mentioned requirements for signal chains in modern IoT sensors the mixed-signal front-end for sensor applications proposed in this work has been developed upon programmable systems on chip (PSoC) [26]. According to the proposed solution, the developed mixed-signal front-end (let us call it PTIC – Programmable Trans-Impedance Converter) combines functions of Transimpedance Amplifier and Programmable Signal Integrator.

III. PROBLEM ANALYSIS

First, let us consider the implementation principle and problems of transimpedance conversion. The principle of such conversion in the front-end of an optoelectronic sensor with a photodiode D_{PH} is depicted in Fig. 1 (left). The circuit contains an operational amplifier OA with a negative feedback circuit (R_I, C_I) that causes the output current I_{INP} of the photodiode D_{PH} to be converted into the output voltage V_{OUT}. The non-inverting input of OA is connected with the zero-potential common chain. Taking into account this fact one concludes that the converter output voltage is $V_{OUT} = I_{INP} \cdot R_I$ to a first approximation.

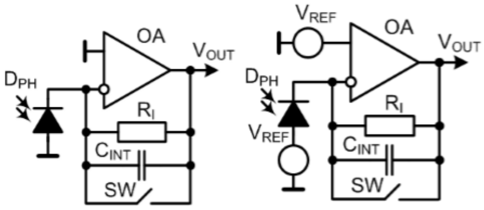

Fig. 1. Transimpedance converters circuits

The advantage of such a transimpedance amplifier is that its input resistance is close to zero ($R_{INP} \rightarrow 0$), which ensures a wide frequency band and high linearity of the input current to output voltage conversion. However, this simple conversion circuit has a drawback: the photodiode capacitance structure influences the transient characteristic badly. As it will be shown, this influence leads to generation of high-frequency transient processes. For minimization of these processes, one uses a capacitor C_{INT} for signal integration and, consequently, frequency correction. For discharging the capacitor C_{INT} and getting the circuit back to its initial state analog the switch SW is used.

Another drawback of such a converter circuit is that a bipolar supply voltage is required. However, the output voltage V_{OUT} is formed in one polarity only, for instance from the common circuit zero-potential to the negative supply voltage. It reduces the dynamic measurement range twice. To solve the problem of the bipolar supply voltage, one forms a reverence voltage V_{REF} in the circuit, which is typically half the unipolar supply voltage (Fig. 1, right). The reference voltage is used in the OA non-inverting input circuit and connection of the photodiode DPH.

When analyzing transimpedance conversion and stability of the TIA circuit operation, we synthesize a SPICE equivalent circuit (Fig. 2, left). It contains an operational amplifier macromodel, X1, and the equivalent circuit of the input current source (of the photodiode, for instance) with the corresponding components I_{INP} and C_{INP}. Fig. 2 (right) shows the result of simulating a transimpedance converter at input current pulses I_{INP} = 1E-6 A, reference voltage V_{REF} = 2.5 V, and two feedback circuit parameters. Two typical cases have been presented. In the first case (s1 – C_{INT} = 1E-12 F) frequency correction is insufficient, which causes parasitic high-frequency generation. On the contrary, in the second case (s2 - C_{INT} = 2E-11 F) frequency correction is excessive, which leads to a significant delay in the output voltage pulse.

Let us emphasize that if the capacitor C_{INT} has a large capacitance, a signal is being integrated for a while. This integration can be used to reduce signal conversion noise. High integration efficiency that enhances the signal-to-noise ratio significantly can be achieved by repeating the conversion multiple times with no capacitor discharging in between. Hence measurement accuracy can be enhanced due to programmed control of a transimpedance converter with the controlled multiple integrations. Such signal conversion is performed (Fig. 3) by switching the corresponding circuits with the period T_{PER} between the delay interval t_{DEL} and the integration interval t_{INT}. Later we will consider subtleties of multiple integrations in detail.

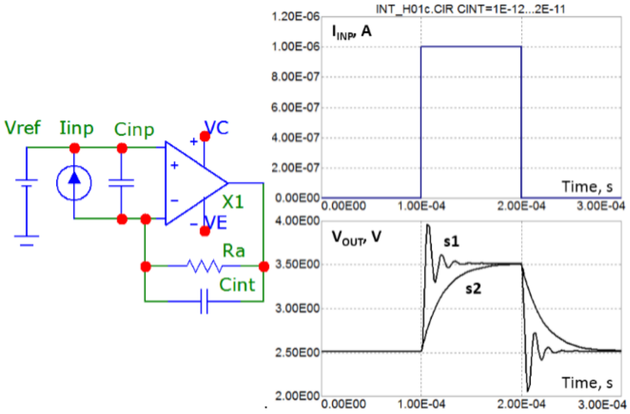

Fig. 2. TIA SPICE model and results simulation

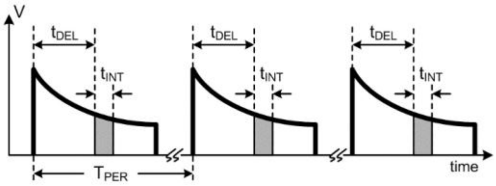

Fig. 3. Signals integration periods

However, the considered measurement conversion is coupled with parasitic effects. The latter are caused by drifting parameters of the feedback circuit and operational amplifier. Let us demonstrate the analysis of these parasitic processes by the example of the integrator simulation (Fig. 4) when there is a drift in the parasitic feedback circuit current (Fig. 4, s1, s2, s3) and off-set voltage (Fig. 4, s4, s5, s6). Thus analysis of the parameters of the considered circuits reveals a number of significant problems whose solution is the objective of this paper.

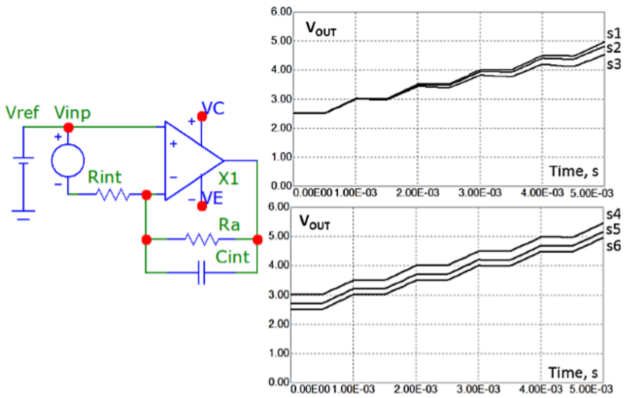

Fig. 4. Integrator SPICE model and results simulation

IV. THE RESULTS OF DEVELOPING THE FRONT-END

Here we present the operation principle of mixed-signal front-end PTIC that solves the problems of measurement techniques enhancement and the dynamic measurement range expansion. As has been said previously, PTIC combines transimpedance amplifier and programmable signal integrator functions with PSoC-based implementation.

A simplified circuit of PTIC analog path is given in Fig. 5. This solution has a distinctive feature – a embedded program controlled integration process with switching the capacitor C_{INT}. Besides the components that have already been considered – the operational amplifier OA, the reference voltage source V_{REF}, the capacitor C_{INT}, and the resistor R_I of the negative feedback circuit – this circuit contains four analog switches.

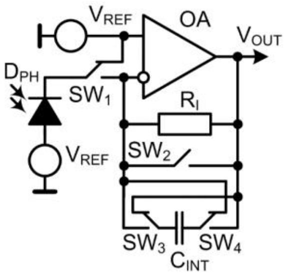

Fig. 5. A simplified circuit of PTIC analog path

The switch SW_1 enables switching of the input circuit including the photodiode D_{PH} between the inverting and non-inverting OA inputs. When connecting D_{PH} to the non-inverting input the integrator is in its passive state at which the current of D_{PH} does not change the charge of the capacitor C_{INT}. This state is denoted with the time interval t_{DEL} in Fig. 3. Connection of D_{PH} to the inverting OA input activates the integration process, and the output voltage is changed by the following value:

$$\Delta V_{OUT} = \frac{1}{C_{INT}} \int_{0}^{t_{INT}} (I_{INP}(t) + I_{OS})dt ,$$

where I_{INP} is the input current, I_{OS} is the parasitic off-set current, t_{INT} is the integration period. The number of integration cycles, N, is defined by the firmware implementation of the measurement algorithm according to the signal parameters, accuracy, and duration of the measurement conversion. The switch SW_2 returns the circuit to its initial state, at which the capacitor C_{INT} is being discharged and the output voltage $V_{OUT} = V_{REF}$ if the OA parameters are ideal. This state is set when the measurement process starts. The switches SW_3 and SW_4 ensure the possibility of switching the polarity of the capacitor C_{INT}.

Fig. 6 shows how the output voltage V_{OUT} is changing during such polarity switching with the period T_{CP}. Not only the useful signal component is demonstrated but also parasitic off-sets V_{OS} of the output voltage and their modulation during polarity switching. Further analog-to-digital conversion should be performed at points V_{10}, V_{1N}, V_{20}, V_{2N},… V_{M0}, V_{MN}, where M is the number of polarity switching cycles. The array of the integrator output voltages are:

$$V_{10} = V_{REF} - V_{OS} ,$$

$$V_{1N} = V_{10} + \frac{M}{C_{INT}} \int_{0}^{t_{INT}} (I_{INP}(t) + I_{OS})dt ,$$

$$V_{20} = V_{10} - \frac{M}{C_{INT}} \int_{0}^{t_{INT}} (I_{INP}(t) + I_{OS})dt , \ldots$$

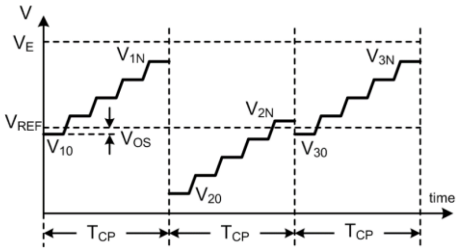

Fig. 6. PTIC signal formation

Then, within the data fusion concept, upon this array and appropriate algorithms for correcting the parasitic drifts of the integration circuit, one separates the useful and parasitic signal components. Besides, the output voltage should be modulated over the entire voltage range of the power supply, in contrast to the previously considered basic simple integrator circuit. This ensures enhancement of the resolution and accuracy of the further analog-to-digital conversion.

To verify the proposed measurement conversion method we have synthesized a SPICE equivalent circuit for the analog path of PTIC (Fig. 7) and obtained simulation results. Some sample results are given in Fig. 8 where numbering 1, 2, 3,… corresponds to the measurement conversion informative signals and points of further analog-to-digital conversion.

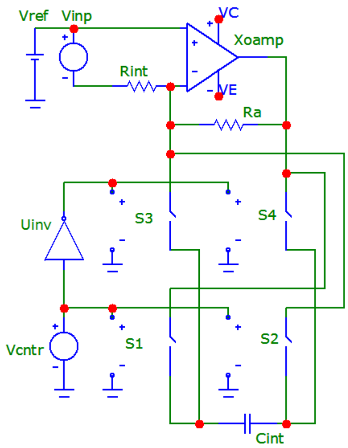

Fig. 7. SPICE equivalent circuit of the PTIC analog path

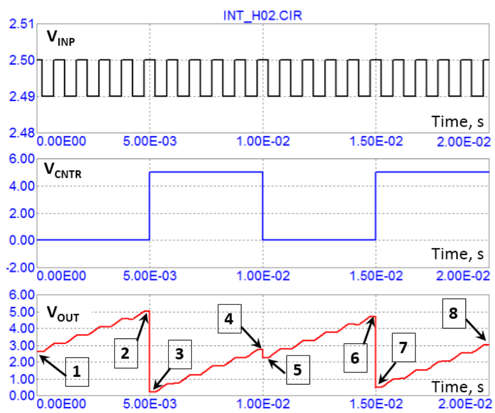

Fig. 8. Sample results of the PTIC analog path simulation

The implementation of the mixed-signal front-end PTIC based on PSoC 5LP is presented in Fig. 9. Sample signals oscillograms during the experimental study and PTIC software windows are shown in Fig. 10.

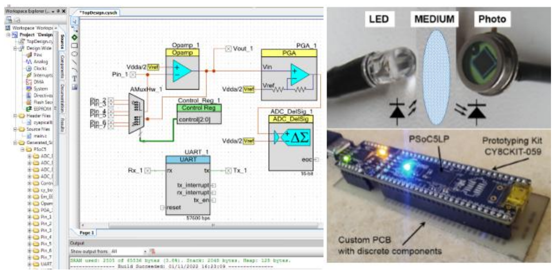

Fig. 9. Implementation of mixed-signal front-end PTIC on PSoC 5LP

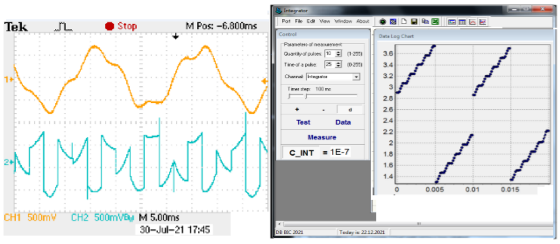

Fig. 10. Signals of PTIC and software

CONCLUSION

The paper discloses the operation principle of Programmable Trans-Impedance Converter (PTIC), a mixed-signal front end that solves the problems of measurement accuracy enhancement and dynamic range expansion. PTIC combines transimpedance amplifier and programmable signal integrator functions with an implementation based on PSoC 5LP (Programmable System on Chip). Simulation and experimental results have been presented. According to the data fusion concept, we form an array of measurement conversion results when switching PTIC operation modes with voltage inversion on the integrating capacitor. Using the array and the corresponding algorithms for the correction of parasitic drifts in the integration circuit, we separate the useful and parasitic signal components. In contrast to the basic integrator circuit, the output voltage in PTIC is modulated over the whole voltage range of the power supply. Due to this fact, one obtains the enhanced resolution and accuracy of further analog-to-digital conversion.

REFERENCES

[1] Hoa Tran-Dang, Dong-Seong Kim (2018), “An information framework for Internet of Things services in physical internet”, IEEE Sensors Journal, vol. 6, pp. 43967 – 43977.

[2] Sung-Hun Jo, Han-Won Cho, Hyung-Joun Yoo (2019), “A fully reconfigurable universal sensor analog front-end IC for the Internet of Things era”, IEEE Sensors Journal, vol. 19, issue 7, pp. 2621 – 2633.

[3] Antoon Bronselaer, Daan Van Britsom, Guy De Tré (2015), “Propagation of Data Fusion”. IEEE Transactions on knowledge and data engineering, vol. 27, issue 5, pp. 1330 – 1342.

[4] Jens Fisseler, Imre Fehér (2010), “Data fusion with probabilistic conditional logic”. Logic Journal of the IGPL, vol. 18, issue 4, p. 488.

[5] Kaibo Liu, Shuai Huang (2016), “Integration of data fusion methodology and degradation modeling process to improve prognostics”, IEEE Transactions on Automation Science and Engineering, vol. 13, issue 1, pp. 344 – 354.

[6] Furqan Alam, Rashid Mehmood, Iyad Katib, Nasser N. Albogami, Aiiad Albeshri (2017),“Data fusion and IOT for smart ubiquitous environments: a survey”, IEEE Access, vol. 5, pp. 9533 – 9554.

[7] Jiandong Zhao, Yuan Gao, Yunchao Qu, Haodong Yin, Yiming Liu, Huijun Sun (2018), “Travel time prediction: based on gated recurrent unit method and data fusion”, IEEE Access, vol. 6, pp. 70463 – 70472.

[8] Tülay Adali, Yuri Levin-Schwartz ,Vince D. Calhoun (2015), “Multimodal data fusion using source separation: application to medical imaging”, Proceedings of the IEEE, vol. 103, issue 9, pp. 1494 – 1506.

[9] Siamac Fazli, Sven Dähne ,Wojciech Samek, Felix Bießmann, Klaus-Robert Müller (2015), “Learning from more than one data source: data fusion techniques for sensorimotor rhythm-based brain computer interfaces”, Proceedings of the IEEE, vol. 103, issue 6, pp. 891 – 906.

[10] Zuozhu Liu, Wenyu Zhang, Shaowei Lin, Tony Q.S. Quek (2017), “Heterogeneous sensor data fusion by deep multimodal encoding”, IEEE Journal of Selected Topics in Signal Processing, vol. 11, issue 3, pp. 479 – 491.

[11] Shesheng Gao, Yongmin Zhong, Wei Li (2011),“Random weighting method for multisensor data fusion”, IEEE Sensors Journal, vol. 11, issue 9, pp. 1955 – 1961.

[12] Manish Kumar, Devendra P. Garg, Randy A. Zachery (2007), “A method for judicious fusion of inconsistent multiple sensor data”, IEEE Sensors Journal, vol 7, issue 5, pp. 723 – 733.

[13] Pei-Hsuan Tsai, Ying-Jun Lin, Yi-Zong Ou, Edward T.-H. Chu, Jane W. S. Liu (2014), “A framework for fusion of human sensor and physical sensor data”, IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 44, issue 9, pp. 1248 – 1261.

[14] Dorota A. Grejner-Brzezinska, Charles K. Toth, Terry Moore, John F. Raquet, Mikel M. Miller, Allison Kealy (2016), “Multisensor navigation systems: a remedy for GNSS vulnerabilities”, Proceedings of the IEEE, vol. 104, issue 6, pp. 1339 – 1353.

[15] Yan Wang,Shuang Cang, Hongnian Yu (2018), “A data fusion-based hybrid sensory system for older people’s daily activity and daily routine recognition”, IEEE Sensors Journal, vol. 18, issue 16, pp. 6874 – 6888.

[16] Simona Barni, Ada Fort, Matteo Becatti, Claudia Fiorillo, Marco Mugnaini, Valerio Vignoli, Tommaso Addabbo, Neri Pucci, Elio Novembre (2017), “Detection of allergen-ige interaction in allergic children through combined impedance and ros measurements”, IEEE Transactions on Instrumentation and Measurement, vol. 66, issue 4, pp. 616 – 623.

[17] M. D. Bryant, S. Yan, R. Tsang, B. Fernandez and K. K. Kumar, "A Mixed Signal (Analog-Digital) Integrator Design," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 59, no. 7, pp. 1409-1417, July 2012, doi: 10.1109/TCSI.2011.2177133.

[18] Xiangyu Chen, Yasuhiro Takahashi (2019), Design of a CMOS broadband transimpedance amplifier with floating active inductor, IEEE Computer Society Annual Symposium on VLSI (ISVLSI), INSPEC Accession Number 18993970.

[19] Xiaojun Bi, Zhen Gu, Qinfen Xu. “Analysis and design of ultra-large dynamic range cmos transimpedance amplifier with automatically-controlled multi-current-bleeding paths”. IEEE Transactions on Circuits and Systems I: Regular Papers, 2019, vol. 66, issue 9, pp. 3266 – 3278. http://doi: 10.1109/tcsi.2019.2924965.

[20] Joon Huang Chuah, David Holburn (2015), “Design of low-noise high-gain CMOS transimpedance amplifier for intelligent sensing of secondary electrons”, IEE Sensors Journal, vol. 15, issue 10, pp. 5997-6004.

[21] Geoffrey Mulberry, Kevin A. White, Brian N. Kim (2018), “A half-shared transimpedance amplifier architecture for high-throughput CMOS bioelectronics”, IEEE Biomedical Circuits and Systems Conference (BioCAS), INSPEC Accession Number.

[22] Josep Ignasi Cairó, Jordi Bonache, Ferran Paredes, Ferran Martín (2017), “Reconfigurable system for wireless power transfer (WPT) and near field communications (NFC)”, IEEE Journal of Radio Frequency Identification, vol. 1, issue 4. pp. 253 – 259.

[23] Martí Boada, Antonio Lázaro, Ramon Villarino, David Girbau (2018), “Battery-less soil moisture measurement system based on a nfc device with energy harvesting capability”, IEEE Sensors Journal, vol. 18, issue 13, pp. 5541 – 5549.

[24] Marti Boada, Antonio Lazaro, Ramon Villarino, David Girbau (2019), “Battery-Less NFC Sensor for pH Monitoring”, IEEE Access, vol. 7, pp. 33226 – 33239.

[25] Andrew DeHennis, Stefan Getzlaff, David Grice, Marko Mailand (2016), “An NFC-Enabled CMOS IC for a Wireless Fully Implantable Glucose Sensor”, IEEE Journal of Biomedical and Health Informatics, vol. 20, issue 1. pp. 18 – 28.

[26] PSoC® 5LP: CY8C52LP Family Datasheet: Programmable System-on-Chip (2020), available at: http://www.cypress.com/.