MultiSensorASIC with CAN-Controller for intelligent sensor systems

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In this paper, an ASIC is presented, which combines a 12bit analogue digital converter with an 8bit micro controller and a CAN controller on a single chip. This solution allows the construction of a wide field of intelligent sensor systems with minimal area requirements and has the capacity for possible data processing. The free programmable micro controller can be used to control the measurement cycle, preprocess the sampled data and transfer it via the CAN-Bus. The implementation of various CAN standard protocols is possible, such as CANopen and DeviceNet. Additionally, a complete system including the proposed ASIC for Wheatstone bridge sensors is described and a simple algorithm for characteristic curve linearization is presented.

Introduction

The development of systems with multiple sensors, decentral intelligence and field bus interface is an important task for the next future. Such systems will be essentially used in applications in the field of environmental measurement techniques and automobile industry.

The progress in the field of microelectronics enables the manufacturing of highly integrated mixed-signal circuits, which combine the advantages of analogue signal processing and digital data entry.

Motivation

Digital bus systems are increasingly being applied for data transfer in process control and process automation. A variety of available sensor systems provide an analogue voltage as an initial signal or a quasi-analog digital signal. An analogue-digital converter translates this initial signal in order to facilitate the transfer of the data via a digital bus system to the process coordination level. At the same time, an additional micro controller for controlling the ADC and bus controller becomes necessary. These additional circuit components require an input of development capacity and costs, which are brought to bear by few manufacturers of sensors only.

Today usually the signal processing is done in a central control station. A high computing power and memory capacity is necessary in this control station. The main disadvantage for such a network is the time between the occurrence of changes of environmental conditions and the control station response. An enormous cut down on data traffic can be reached by transmitting only the compressed data in the sensor node.

ASIC characteristics

For this reason, an ASIC was developed at the Fraunhofer Institute for Microelectronic Circuits and Systems within the framework of the joint project "Modular Pressure Sensor System" and contains an efficient 12 bit ADC with 4 analogue inputs, an 8 bit micro controller core, peripheral components and a CAN bus controller. By connecting this circuit to available sensors, the user is able to apply this wide range of sensors to a bus and to offer a reasonable solution. The additional opportunities of processing digital signals in the freely programmable micro controller architecture do considerably expand the fields of application.

The integrated micro controller core IMS16Cxx is in architecture, instruction set and timing compatible to the Midrange family PIC16Cxx from Arizona Microchip. This solution allows the usage of all development tools for software programming. In addition, it is possible to reuse software for several projects. The implemented peripheral components are also compatible to the original ones. The micro controller periphery includes three freely programmable 8bit digital IO-Ports, three programmable counter/timer, a basic I^{2}C interface and a PWM module. Many internal and external events, such as timer overflow or CAN controller receive can be controlled by the implemented interrupt system. A sleep mode can be used to reduce the power consumption in phases where the system waits for external events or commands. FIGURE 1 depicts the block diagram from the developed ASIC.

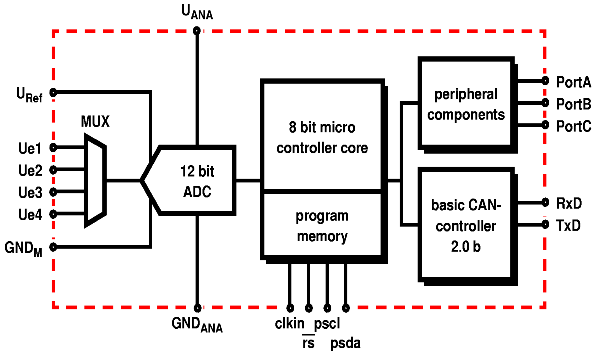

FIGURE 1   MSA Block Diagram

The ADC converts a voltage from four different analogue inputs with the feature of a programmable sampling time. The minimum conversion time requires 172 µs. To control the ADC two techniques can be applied: polling by the conversion complete bit or by event of the associated interrupt flag. The ADC reference voltage has taken connected to an external pin to allow absolute or ratio metric measurement of the input voltage.

The integrated CAN controller realizes the standard CAN protocol 2.0b and is qualified by the BOSCH test data Rev.2.1/1993. To connect the ASIC to the CAN bus a common transceiver circuit is required. The controller is able to send and receive standard or extended frames with a maximum data rate up to 1 Mbit per second. The data rate is programmable in a wide range. All CANopen standard data rates are supported by a main clock of 4 MHz.

The chip dimensions are 4100 x 2900 microns in an in-house 0.5-micron CMOS technology. FIGURE 2 shows a chip photo of the developed ASIC.

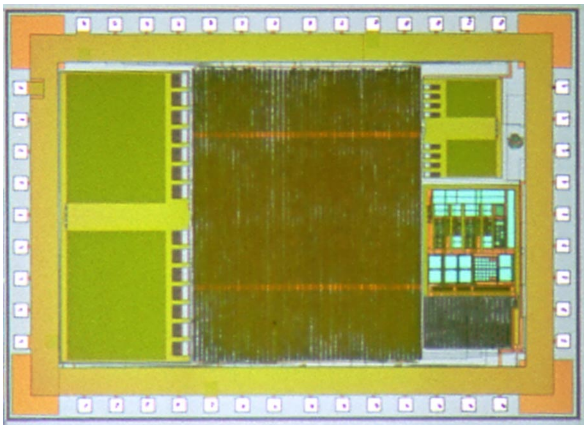

FIGURE 2   MSA chip photo

A system performance of 2 MIPS can be achieved by a main clock of 16 MHz. The supply voltage of the ASIC is 3.3 V and the current consumption by 16 MHz main clock value is below 2 mA.

The internal program memory space is 1024 instruction words. Following the system reset the user program is loaded via the I^2C interface from an external serial E^2prom by an internal boot loader. The boot mechanism can also be used to change program parts or the complete program during the operation. This opportunity increases the virtual usable program memory range. Additionally, parts of the external serial E^2prom can be used for data storage, for instance for calibration data und manufactory identification information.

Signal path

Many sensors typically use a Wheatstone bridge configuration, e.g. pressure sensors, load cells, or thermistors. These sensors provide a low level, differential output signal. The designer is challenged with the problem to capture this small signal and to convert it to a digital format that gives a 12bit representation of the signal. Such a resolution is necessary for good result accuracy. The main problem is to place the sensor output voltage in the input range of ADC. Typically, an instrumentation amplifier (IA) is used to amplify and convert the small differential output voltage in a single ended voltage. The signal then passes through a low pass filter. The low pass filter eliminates out-of-band noise and unwanted frequencies in the system before the conversion is performed.

In FIGURE 3 the block diagram for the sensor signal-conditioning path depicted.

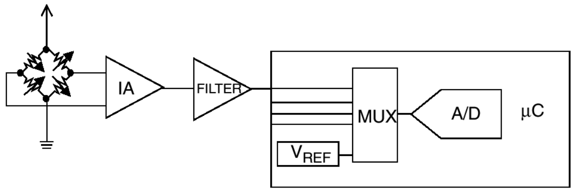

FIGURE 3 Signal Path Block Diagram

To realize an instrumentation amplifier often three operational amplifiers are used. The advantages of such a solution are to achieve an independent common-mode rejection from the gain and over the frequency range. With this circuit configuration, two of the three amplifiers treat the two input signals. The third amplifier is used to subtract the two amplified input signals, thereby providing a single ended output. The reduced transfer function, if $R_{F1} = R_{F2}$, $R_1 = R_3$ and $R_2 = R_4$ is equal to:

$$V_{OUT} = \left(V_{IN+} - V_{IN-}\right)\left(1 + \frac{2R_F}{R_G}\right) + V_{REF} \,.$$

The gain of the instrumentation amplifier is controlled by the common resistor R_G. Quad amplifiers are typically used in the three op-amp instrumentation amplifier discrete designs because of the matching qualities of amplifiers with the same silicon. The fourth amplifier can be used to realize the following low pass filter. The complete circuit of the analogue signal path is shown in FIGURE 4

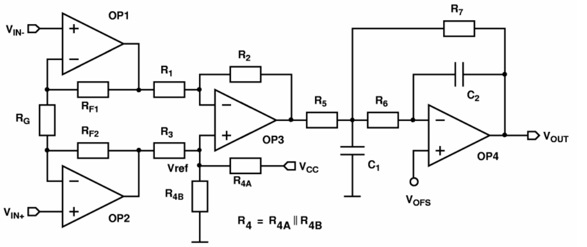

FIGURE 4 Signal path circuit

The second order Multiple Feedback circuit implementation needs a voltage reference at the non-inverting input of the amplifier. Then this reference voltage is adjustable, it is possible to control the sensor offset by the micro controller. This solution can be used by the sensor calibration process to correct fabrication specific sensor tolerances.

A temperature sensor is connecting to the analogue input to measuring the environment temperature. This information is needed to correct the temperature dependence of the sensor output signal digital. The other two analogue input channels are used to detect systems errors, e.g. supply voltage underflow and bridge pull-off.

System realization

In FIGURE 5 the block diagram of the realized system circuit is depicted. It includes all necessary components to enable a connection from a Wheatstone bridge sensor to the CAN bus.

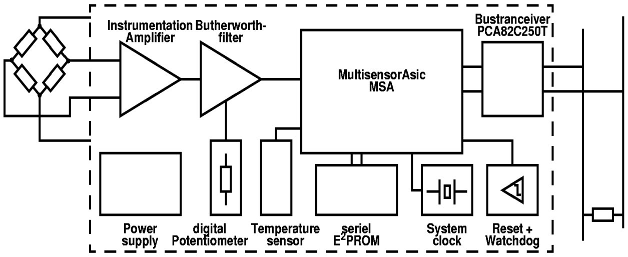

FIGURE 5 System Block Diagram

As additional components the temperature sensor and a watchdog timer are included. A simple programming connector for the serial E^2prom enables an in circuit-programming feature. The sensor bridge can be connected direct to the board. A jumper can switch the reference voltage for the ADC from absolute to relative metric. The gain of the instrumental amplifier is selectable by the value of one resistor. In FIGURE 6 a photo of the printed circuit board in shown. The dimensions without the SUB-D connector are 48 x 20 millimetres.

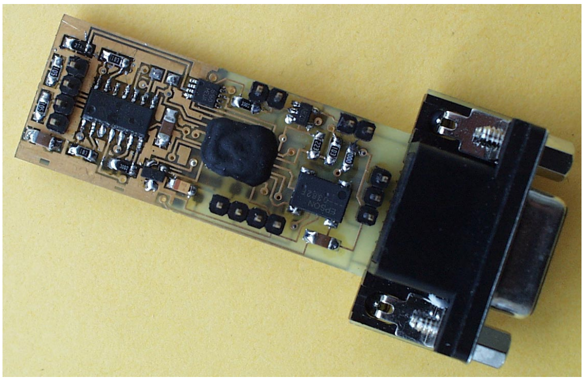

FIGURE 6 Printed circuit board photo

The supply voltage of the printed circuit is 5 volt and the current consumption depending of the CAN bus data rate and load is 20 to 70 mA.
Common Wheatstone bridge sensor can easy be adapted to this system, because it has small dimensions, a minimal weight, low energy consumption and a good system performance.

Characteristic curve linearization

The presented sensor system made it possible to correct a nonlinear characteristic curve of the sensor before the measurement results were be transmitted over the CAN bus. To reduce the necessary response time an efficient linearization algorithm must be found.
A typical series of measurements for a barometric pressure sensor is shown in the following table.

p/mBar	300	400	500	600	700	800	900	1000
ADUval	765	969	1174	1379	1582	1786	1989	2192
p/mBar	1100	1200	1300	1400	1500	1600	1700	
ADUval	2394	2596	2798	2998	3199	3398	3597	

The simplest way is to compute the correct data with a linear function between all access points. The main disadvantage is the required memory space for the coefficients and the necessary search algorithm to find the exact range.
A better solution is to use the polynomial approximation, to find one function for the complete measuring range. Generally, the function is represented with a polynomial of order $1 \le q < n$ by

$$p(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \ldots + a_q x^q .$$

Under the condition

$$S(a_0, \ldots a_N) = \sum (y_i - p(x_i))^2$$

to calculate the minimum, the follow equation system

$$\left(\sum_1^n x_i^0\right) a_0 + \left(\sum_1^n x_i^1\right) a_0 + \ldots + \left(\sum_1^n x_i^q\right) a_0 = \sum_1^n y_i x_i^0$$
$$\left(\sum_1^n x_i^1\right) a_0 + \left(\sum_1^n x_i^2\right) a_0 + \ldots + \left(\sum_1^n x_i^{q+1}\right) a_0 = \sum_1^n y_i x_i^1$$
$$\ldots$$
$$\left(\sum_1^n x_i^q\right) a_0 + \left(\sum_1^n x_i^{q+1}\right) a_0 + \ldots + \left(\sum_1^n x_i^{q+q}\right) a_0 = \sum_1^n y_i x_i^q$$

must be solved to get the coefficients $a_0, \ldots, a_q$. The error Δ can determined by

$$\sqrt{\frac{S(a_0, \ldots, a_q)}{n}} = \sqrt{\frac{1}{n} \sum_1^n (y_i - p(x))^2} .$$

For the example series of measurements the calculated coefficients are shown in follow table.

q	a_0	a_1	a_2	a_3	a_4	Δ
1	-0.809	0.0049				0.01857
2	-0.700	0.0048	2.71e^{-8}			0.00256
3	-0.729	0.0048	1.53e^{-9}	3.91e^{-12}		0.00160
4	-0.721	0.0048	1.72e^{-8}	-1.23e^{-12}	5.89e^{-16}	0.00159

A polynomial of third or fourth order gives an accurate result in the complete measuring range.
The evaluation of a polynomial with the degree n requires $2n-1$ multiplications and n additions, and it also require further instructions to store and retrieve intermediate results from memory. One way to save expensive micro controller resources is evaluating $p(x)$ as follows:

$$p(x) = (\ldots(a_q x + a_{q-1})x + \ldots)x + a_0 .$$

Start with a_q, multiply by x, add a_{q-1}, multiply by x, …, multiply by x, and add a_0. This form of the computation is usually called "Horner's rule". The entire process requires

n multiplications and n additions. Furthermore, there is no need to store partial results, since each quantity arising during the calculation is used immediately after it has been computed.
Polynomials of degree $n > 3$ can be evaluated in less than n multiplications, when one precomputes some auxiliary coefficients. For the polynomial

$$p(x) = a_o + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4$$

where $a_4 > 0$, can be evaluated with 3 multiplications and 5 additions as follows:

$$p(x) = \left[(Ax+B)^2 + Ax + C\right]\left[(Ax+B)^2 + D\right] + E$$

where A, B, C, D and E are to be precomputed by

$$A = (a_4)^{\frac{1}{4}}$$

$$B = \frac{a_3 - A^3}{4A^3}$$

$$D = 3B^2 + 8B^3 + \frac{a_1 A - 2a_2 B}{A^2}$$

$$C = \frac{a_2}{A^2} - 2B - 6B^2 - D$$

$$E = a_0 - B^4 - B^2(C + D) - CD$$

In the case, where $a_4 < 0$ the polynomial is transformed to

$$-p(x) = (-a_0) + (-a_1 x) + \left(-a_2 x^2\right) + \ldots + \left(-a_4 x^4\right)$$

and the precomputed auxiliary coefficients can be solved in the same manner.
This method allows to program an efficient algorithm for the sensor calibration. The micro controller program includes a 32bit fixed point arithmetic to calculate the ADC result in actually pressure value. The polynomial solve algorithm and fixed-point algorithm requires 269 instruction words. A value is computed on a time of 1.16 ms by an 8 MHz micro controller main clock.
The other program space is used to implement a minimal CANopen slave. It includes the NMT services Reset Node, Reset Communication, Boot Up, Enter Pre-Operational State, Start Remote Node, Stop Remote Node and Node Guarding or Heartbeat Service. The slave node ID is fixed in the E^{2}prom memory. The software supports one SDO server and up to four PDO's for transmit and receive.

Measurement results

The next figures depict various measurement data from the presented system circuit. In FIGURE 7 the uncorrected ADC values is shown. The signal path has an accurate straight-line characteristic.

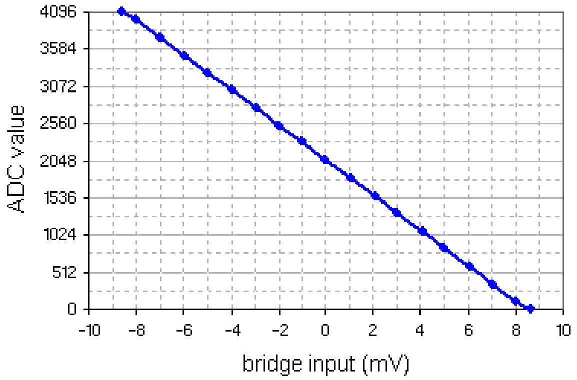

FIGURE 7 ADC value by a low input signal

FIGURE 8 show the temperature dependence of the signal path with a constant input voltage as input source and with a force sensor as sensor input. The ADC values are also uncorrected.

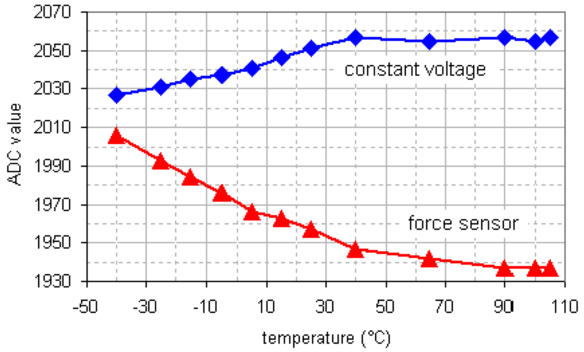

FIGURE 8 Temperature dependence

This temperature dependence can be compensated in the digital domain.

Summary and Outlook

The presented ASIC allows the design of a wide field of electrical sensors suitable for a connection to the CAN bus. Because of the small size of this ASIC, the construction of microminiature assemblies is possible and especially signal processing algorithms can be implemented to increase the quality of the measured sensor signal. Higher protocol application layers, e.g. CANopen or DeviceNet are implementable in a MSA based system.

The proposed signal path allows the processing of small differential input values and the system is able to correct nonlinear characteristic curves and offset errors.

A second realized system in shown in FIGURE 9 . This system combines a common pressure transmitter with the developed ASIC solution on a printed circuit. The objectives in doing so have been smallest geometrical dimensions and low energy consumption.

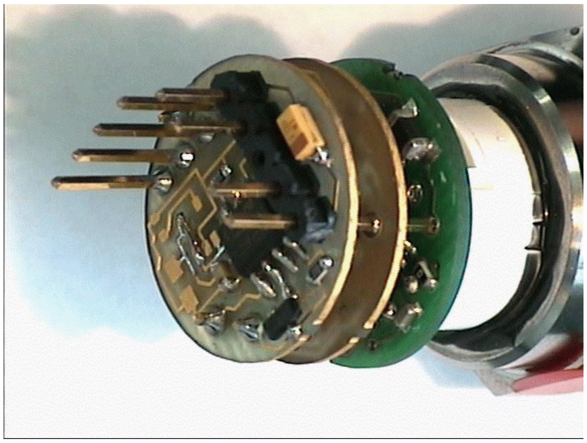

FIGURE 9 Pressure Sensor with CAN-Interface

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