SECTION 9
SMART SENSORS
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4-20MA CONTROL LOOPS

Industrial process control systems make extensive use of 4-20mA control loops. Many sensors and actuators are designed precisely for this mode of control. They are popular because they are simple to understand, offer a method of standardizing the sensor/control interface, and are relatively immune to noise. Figure 9.1 shows how a remote actuator is controlled via such a loop from a centrally located control room. Notice that the transmitter output to the actuator is controlled by a DAC, in this case, the AD420. The entire process is under the control of a host computer which interfaces to the microcontroller and the AD420. This diagram shows only one actuator, however an actual industrial control system would have many actuators and sensors. Notice that the "zero scale" output of the DAC is actually 4mA, and "fullscale" is 20mA. The choice of a non-zero output current for "zero scale" allows open circuit detection at the transmitter and allows the loop to actually power the remote sensor if its current requirement is less than 4mA.

Figure 9.1

Many of the control room circuits are directly powered by the loop power supply which can range from approximately 12V to 36V. In many cases, however, this voltage must be regulated to supply such devices as amplifiers, ADCs, and microcontrollers. The loop current is sensed by the R_{SENSE} resistor which is actually a part of the AD420. The internal DAC in the AD420 is a sigma-delta type with 16-bit resolution and monotonicity. The serial digital interface allows easy interface to the microcontroller.

Figure 9.2 shows a 4-20mA output "smart" sensor which is completely powered by the loop power supply. In order for this to work, the sum total of all the circuits under loop power can be no more than 4mA. The heart of the circuit is the AD421 loop-powered 16-bit DAC. The internal 4-20mA DAC current as well as the rest of the return current from the AD421 and the other circuits under loop power flows through the R_{SENSE} resistor. The sensing circuit compensates for the additional return current and ensures that the actual loop return current corresponds to that required by the digital code applied to the DAC through the microcontroller. The sensor output is digitized by the AD7714/AD7715 sigma-delta ADC. Note that the total current required by all the circuits under loop power is less than the required 4mA maximum. The AD421 contains a regulator circuit which controls the gate of the external DMOS FET and regulates the loop voltage to either 3V, 3.3V, or 5V to power the loop circuits. In this way the maximum loop supply voltage is limited only by the breakdown voltage of the DMOS FET.

Figure 9.2

The HART protocol uses a frequency shift keying (FSK) technique based on the Bell 202 Communications Standard which is one of several standards used to transmit digital signals over the telephone lines. This technique is used to superimpose digital communication on to the 4-20mA current loop connecting the control room to the transmitter in the field. Two different frequencies, 1200Hz and 2200Hz, are used to represent binary 1 and 0 respectively. These sinewave tones are superimposed on the DC signal at a low level with the average value of the sinewave being zero. This allows simultaneous analog and digital communications. Additionally, no DC component is added to the existing 4-20mA signal regardless of the digital data being sent over the line. The phase of the digital FSK signal is continuous, so there are no high frequency components injected onto the 4-20mA loop. Consequently, existing analog instruments continue to work in systems that implement HART, as the lowpass filtering usually present effectively removes the digital signal. A single pole 10Hz lowpass filter effectively reduces the communication signal to a ripple of about ±0.01% of the fullscale signal. The HART protocol specifies that master devices like a host control system transmit a voltage signal, whereas a slave or field device transmits a current signal. The current signal is converted into a corresponding voltage by the loop load resistor in the control room.

Figure 9.3 shows a block diagram of a smart and intelligent transmitter. An intelligent transmitter is a transmitter in which the function of the microprocessor are shared between deriving the primary measurement signal, storing information regarding the transmitter itself, its application data, and its location, and also managing a communication system which enables two-way communication to be superimposed on the same circuit that carries the measurement signal. A smart transmitter incorporating the HART protocol is an example of a smart intelligent transmitter.

Figure 9.3

The HART data transmitted on the loop shown in Figure 9.3 is received by the transmitter using a bandpass filter and modem, and the HART data is transferred to the microcontroller's UART or asynchronous serial port to the modem. It is then waveshaped before being coupled onto the AD421's output through the coupling capacitor C_C. The block containing the Bell 202 Modem, waveshaper, and bandpass filter come in a complete solution with the 20C15 from Symbios Logic, Inc., or HT2012 from SMAR Research Corporation.

INTERFACING SENSORS TO NETWORKS

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The HART protocol is just one of many standards for industrial networking. Most industrial networks run independently of analog 4-20mA lines, but many are intended to interface (directly or indirectly) with smart sensors as shown in Figure 9.4.

Figure 9.4

These industrial networks can take many forms. The “field network” in Figure 9.4 represents a wide bandwidth distributed network such as Ethernet or Lonwork. A field network by this definition is not generally intended to interface directly with a smart sensor. A "device network," on the other hand, is intended specifically to interface to smart sensors. Most "device networks" (such as ASI-bus, CAN-bus, and HART) also provide power to smart sensors on the same lines that carry serial data. Some of today's more popular industrial network standards are listed in Figure 9.5. Each offers its own advantages and disadvantages, and each has a unique hardware implementation and serial protocol. This means that a smart sensor designed for one industrial network is not necessarily compatible with another.

Figure 9.5

Since factories and many other networked environments often have multiple networks and sub-networks, a far more flexible solution is one where sensors are "plug and play" compatible with all different field and device networks. The goal of the IEEE 1451.2 sensor interface standard is to make network independent sensors a reality.

Figure 9.6 shows the basic components of an IEEE 1451.2 compatible system. The smart sensor (or smart actuator) is referred to as a "STIM" (Smart Transducer Interface Module). It contains one or more sensors and/or actuators in addition to any signal conditioning and A/D or D/A conversion required to interface the sensors/actuators with the resident microcontroller. The microcontroller also has access to nonvolatile memory that contains a "TEDS" field (or Transducer Electronic Data Sheet) which stores sensor/actuator specifications that can be read via the industrial network. The NCAP (Network Capable Application Processor) is basically a node on the network to which a STIM can be connected. At the heart of the IEEE 1451.2 is the standardized 10-wire serial interface between the sensor and the NCAP, called the TII (or Transducer Independent Interface). In an environment with multiple networks, the TII allows any STIM to be plugged into any NCAP node on any network as shown in Figure 9.7. When the STIM is first connected to the new NCAP, the STIM's digital information (including its TEDS) is made available to the network. This identifies what type of sensor or actuator has just been connected and indicates what input and output data are available, the units of input an output data (cubic meters per second, degrees Kelvin, kilopascals, etc.), the specified accuracy of the sensor (±2 degrees °C, etc.), and various other information about the sensor or actuator. This effectively eliminates the software configuration steps involved in replacing or adding a sensor, thereby allowing true "plug and play" performance with network independence.

Figure 9.6

Figure 9.7

Most smart sensors (not limited to 1451.2 STIMs) contain the primary components shown in Figure 9.8. The Analog Devices MicroConverter™ products are the first to incorporate all of these components on a single chip (Figure 9.9).

Figure 9.8

Figure 9.9

The three primary functions of every MicroConverter™ product (Figure 9.10), are: high resolution analog-to-digital and digital-to-analog conversion, non-volatile FLASH EEPROM for program and data storage, and a microcontroller. Of the first three MicroConverter™ products to be introduced, all contain a 12-bit voltage output DAC, a precision bandgap voltage reference, and an on-chip temperature sensor. Figure 9.11 lists the basic analog I/O functionality of each. All three have exactly the same FLASH memory and microcontroller core, some features of which are highlighted in Figures 9.12 and 9.13.

Figure 9.10

Figure 9.11

Figure 9.12

Figure 9.13

The highest resolution MicroConverter™ product is the ADuC816. Its analog front end consists of two separate ΣΔ ADC converters with a flexible multiplexing scheme to access its two differential input channels as illustrated in the functional block diagram of Figure 9.14. The "primary channel" ADC is a 24-bit ΣΔ converter that offers better than 16-bit signal-to-noise ratio. This primary channel also features a programmable gain amplifier (PGA), allowing direct conversion of low-level signals such as thermocouples, RTDs, strain gages, etc. Two "burn out" current sources can be configured to force a very small current through the sensor to detect open circuit conditions when the sensor may have been disconnected or "burned out". The primary channel ADC can be multiplexed to convert both of the differential input channels, or the second differential input can be routed to the "auxiliary channel" ADC which is a 16-bit ΣΔ converter with better than 14-bits of signal-to-noise ratio. This auxiliary channel can also be used to read the on-chip temperature sensor. A pair of 200µA current sources ($I_{EXC}1$ & $I_{EXC}2$) can be used to provide excitation for sensors such as RTDs. Both ADCs as well as the DAC can be operated with the internal 2.5V bandgap reference, or with an external reference.

Figure 9.14

The primary performance specifications of the ADuC816 are given in Figure 9.15. All ADC specifications here refer to the "primary channel" ADC. Exceptionally low power dissipation can be achieved in low bandwidth applications by keeping the ADuC816 in the power down mode for much of the time. By using an internal PLL, the chip derives its 12MHz clock from a 32kHz watch crystal. When in power down mode, the 12MHz clock is disabled, but the 32kHz crystal continues to drive a real-time counter which can be set to wake the chip up at predefined intervals. The ADuC816 can also be configured to wake up upon receiving an external interrupt.

Figure 9.15

The ADuC812 offers a fast (5µs) 12-bit 8-channel successive approximation ADC with many of the same peripheral features of the ADuC816. The functional block diagram (Figure 9.16) illustrates its primary components. Since the 8-bit × 1MIPS microcontroller core cannot generally keep up with the 12-bit 200kSPS ADC output data, a DMA (direct memory access) controller is included on the ADuC812 to automatically write ADC results to external memory, thus freeing the microcontroller core for other tasks. Whether in DMA mode or in normal mode, the ADuC812 conversions can be triggered by several means. Conversions can be triggered in software, or a timer can be set to automatically initiate a conversion each time it overflows, thereby allowing precise control of sampling rate. A hardware convert-start can also be utilized for applications requiring critical timing.

The ADuC812 contains two 12-bit DACs that can be powered on or off independently of each other, and can be updated either simultaneously or independently. The DACs can be configured for an output range of 0 to V_{DD} or 0 to V_{REF}, where V_{REF} can be either the internal 2.5V bandgap reference or an externally applied reference voltage. The internal reference, if used, can also be buffered to drive external circuitry.

Figure 9.16

Figure 9.17 lists some primary performance specifications of the ADuC812. The power specifications are given assuming a 12MHz crystal. Since all on-chip logic is static, the clock can be slowed to any frequency, allowing exceptionally low power dissipation in low bandwidth applications. For applications requiring greater speed, the clock can be increased to as much as 16MHz to achieve slightly faster microcontroller operation (1.33MIPS).

Figure 9.17

Figure 9.18

Because MicroConverter™ products are based on an industry standard 8052 core, developers can draw from a wealth of software, reference material, and third party tools that already exist for 8051/8052 MCUs. The MicroConverter™ web site provides links to many sources of such material, in addition to offering downloads of internally generated tools, data sheets, and example software.

Figure 9.19

To get any designer or developer started with a MicroConverter product, Analog Devices offers a QuickStart™ Development Kit which contains all of the necessary features for many designers to complete a design without the added expense of additional simulation or in-circuit emulation packages.

Figure 9.20

For designs that require the added power of full in-circuit emulation, or the added ease of C coding with mixed-mode debugging, Keil and Metalink offer the first of many third party tools to be endorsed by Analog Devices. These tools are fully compatible with the MicroConverter™ products, and other third party developers will soon offer additional MicroConverter™-specific tools to further expand the options available to designers.

Figure 9.21

While the ADuC812, ADuC816, and ADuC810 offer a mix of features and performance not previously available in a single chip, future MicroConverter™ products will offer even greater levels of integration and functionality. Larger FLASH memory versions will be offered to compliment one or more of the existing products. Additional hardware communications may also be added to future MicroConverter™ products to allow direct communication with industrial networks or PC platforms. Eventually, there will be MicroConverter™ products with greater MCU processing bandwidth. However, comparing these devices to basic microcontrollers is a mistake. The performance level of MicroConverter™ analog I/O is far superior to that available in microcontrollers with analog I/O ports.

Figure 9.22

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