Device Integration of CAN Controller, Data Converters, and ISP Non-Volatile Memory Facilitates Smart Sensor Connectivity to Controller Area Networks

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Abstract: IEEE 1451 specifies smart sensor function and connectivity to networks. This marks an evolution from central system control by a master processor with "dumb" nodes to distributed control networks of "smart" sensors. Controller Area Network (CAN) is a multi-master protocol designed for communications in real-time, distributed control systems. Therefore, it is logical that CAN be used to network smart sensors in these systems. The move to IEEE 1451 smart sensor nodes in distributed control systems with CAN connectivity increases the complexity and therefore size and cost per node. To address these size and cost issues, mixed-signal microcontrollers are now offered that integrate a CAN controller, non-volatile memory, and quality analog data converters. Such devices can offer integration of IEEE 1451 functions for smart sensor "plug and play" connectivity to controller area networks. Integration makes distributed control networks feasible.

INTRODUCTION

Modern distributed real-time control systems are used to manage large processes. Such systems must measure and manipulate parameters at various points within the system, and these nodes must communicate in order to control a process. Controller Area Network (CAN) is a communications protocol designed for such systems, forming "smart," robust systems ideal for use in automotive and industrial control. As such systems become more sophisticated, the nodes that measure and control parameters (or *transducers*) become more complex. Such transducers are often referred to as *smart sensors*.

While CAN has been widely adopted, the idea of the smart sensor has been slow to be standardized. IEEE 1451 attempts to solve the problem of smart sensor standardization. With these sensors defined and CAN to facilitate communication between them, the stage has been set to build distributed control systems with "plug and play" nodes. However, these systems require sophisticated electronic components at low-cost. Many devices now integrate much of the functionality (MCU, analog measurement and output, non-volatile memory, CAN controller) required to produce low-cost, small form-factor transducer nodes. Integrated CAN controllers with MCU, ISP FLASH/EEPROM, ADC's, and DAC's make smart sensor networks feasible.

SMART SENSORS

"Sensors" in distributed control systems are often referred to as *transducers* to include both *sensors* and *actuators*. While sensors have been used for many years, the idea of a "smart" sensor is relatively new, and not well defined. However, there are a few common ideas that most seem to agree upon when discussing smart sensors:

- A smart sensor can store information, usually about itself.
- A smart sensor has communication ability.
- A smart sensor can make decisions based on measurements.

In general, a smart sensor does more than simply sense or actuate – it performs a higher-level function and can communicate with other nodes to take action based on measurements other than its own. Because the sensor itself may perform only portions of the above-described functionality, the sensor node or module will typically have some local processing such as an MCU or digital signal processor (DSP). Local processing facilitates both the manipulation of data and communication with a network such as CAN.

If a standard is to be made for smart sensors, then a minimum function must be defined. One example is the storage of sensor information that can be downloaded by local processing when installed in a network, facilitating the so-called plug and play functionality.

IEEE 1451 defines a standard way in which transducer information is formatted and stored. In this way, a transducer can be plug and play enabled. Because transducers use a variety of communications methods (e.g.,CAN, Ethernet, RS-485, LIN, Profibus, etc.), IEEE 1451 separates the sensor from the burden of system bus communications. Instead, a *Network Capable Application Processor* (NCAP) takes care of this and the sensor needs only to communicate with the NCAP using an IEEE 1451 defined method. The sensor manufacturer then needs only to produce a *Smart Transducer Interface Module* (STIM) with a standardized interface capable of communicating with the NCAP.

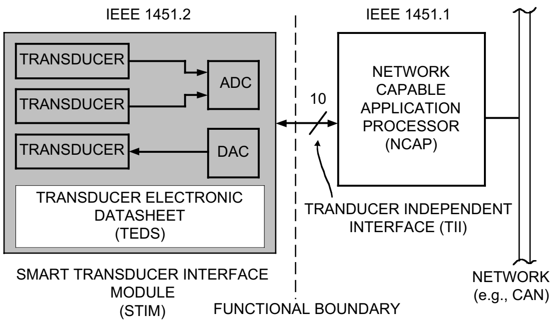

Figure 1. IEEE 1451 STIM and NCAP

This communication between the STIM and the NCAP is defined in IEEE 1451.2, called the *Transducer Independent Iinterface* (TII). TII requires 10 wires and is similar to serial peripheral interface (SPI)[1], with added signaling wires. Also defined in IEEE 1451.2 is the *Transducer Electronic Datasheet* (TEDS). The TEDS is perhaps the most defining attribute of the IEEE 1451 standard. The TEDS contains transducer information in a defined format and is stored in the transducer in non-volatile memory.

IEEE 1451.1 specifies the function of the NCAP and 1451.2 specifies the TEDS format and TII communications. While IEEE 1451.1 and 1451.2 laid the foundation for standard smart sensors, the STIM and NCAP (and the 10-wire TII) have yet to gain wide acceptance in commercial smart sensor applications. However, sensor manufacturers and sensor users accepted the idea of an on-sensor TEDS.

Today, new IEEE 1451 standards are being drafted to more closely match commercially available products. One such standard is IEEE 1451.4 which supports a more simple approach with the flexibility of using an interface that is compatible with commonly used sensors. While compatible with IEEE 1451.1 and 1451.2, the functional boundary of the transducer and NCAP are moved to allow the use of an IEEE 1451.4 *Mixed-Mode Interface* (MMI).

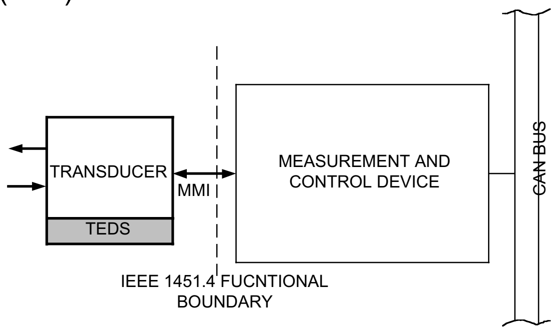

Figure 2. IEEE 1451.4 and Mixed-Mode Interface

This interface is essentially a 1-wire interface[2] (actually two wires, a signal and ground) that can transfer TEDS data over a pre-existing analog output wire (e.g., a current loop) in a digital mode, or directly via dedicated digital output signals. This less complicated approach moves most of the burden of the data processing task to the local host processor, while maintaining plug and play capability by keeping a TEDS in a non-volatile memory device on the sensor (usually EEPROM). In IEEE 1451.4, the sensor output is not digitized on the transducer module (and sent over the digital TII to the NCAP), but left as an analog signal. This represents a smaller step towards IEEE 1451 industry acceptance and is already in use. Because the TEDS (and a TEDS template description language) can contain a great deal of transducer specific data (e.g., calibration and sensitivity data), greater accuracy in measurements is possible. At a minimum, the end-user is relieved of entering transducer information manually into a data acquisition system. In these systems, a new functional boundary is created: The *transducer* and *Measurement and Control* device interface using the MMI (as opposed to the NCAP and STIM). (See Figure 2).

Other IEEE 1451 interface standards are now being developed. Increasing sophistication of integrated circuits at lower costs and a standard method of implementing local smart sensor nodes will pave the way for cost effective and scalable distributed control systems. Building such systems requires a reliable and smart network for communications among smart transducer nodes: Controller Area Network.

CAN: The Smart Sensor Communications Network

While smart transducers are the building blocks of distributed control systems, these sensors and actuators must communicate with each other in order to implement a process. The Controller Area Network protocol is designed for real-time distributed control, making CAN a natural choice to use with smart sensors.

CAN networks allow high bit rates of up to 1 Mbps (CAN 2.0B), with error control features and fault confinement. Additionally, CAN utilizes 29-bits (with masking) for unique message identifiers that are used in network arbitration. The non-destructive bitwise arbitration scheme supports multi-master operation. This, along with priority encoded into message identifiers, allows critical information to be transmitted while less critical transducers reside on the same network. In this way, CAN is very flexible and scalable.

While the CAN specification does not define a physical layer (only MAC and LLC layers), there exists robust physical layer specifications in use such as ISO 11898-2 that are reliable in electrically noisy environments – typical in smart sensor applications. While CAN only specifies only the MAC and LLC layers of the OSI model, there are higher-layer protocols (HLP) available such as CANopen and DeviceNet. While smart sensors provide great flexibility in building a network of transducer nodes, these HLP's facilitate flexible and easy to design networks of these CAN nodes that can be used to send, receive, and request information. For example, CANopen features device synchronization, autoconfiguration of the network, and event driven data transfer.

CAN network features helpful in smart sensor networks:

- Error control – both framing errors and bit-level errors, with error frame signaling, and CRC to ensure sensor data integrity
- Flow Control – both remote frames (data request) and overload frames for sensor node distributed control
- Broadcast and Priority Control – sensor messages with high priority identifiers for critical system data and control
- Higher-Layer Protocols – Highly configurable and some support electronic data sheets (analogous to the IEEE 1451.2 TEDS)
- High speed and fault-tolerant physical layers – useful in smart sensor system environments for high reliability

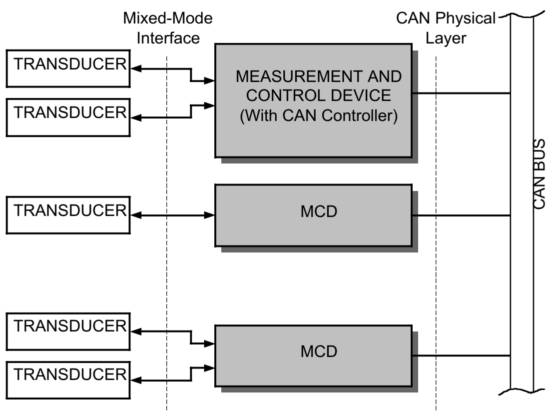

Figure 3. Smart Sensors and CAN

With error control, flexible arbitration, message identification, and robust physical layers, the CAN bus is one of the best solutions for building a network of smart transducers.

BUILDING TRANSDUCER NODES IN A CONTROLLER AREA NETWORKS: INTEGRATION

Traditional real-time control systems use a network of slave nodes and a central master processor of some kind to control a process. The idea of the smart sensor and of the controller area network is to build instead a distributed control system, where there are multiple masters each with a transducer that has local processing, data storage, and communication ability – a "smart" sensor. The tradeoff is that such system nodes (i.e., points of measurement and control) are more complex, increasing the cost and size of each node compared with traditional systems of "dumb" sensors and a central master processor. Integration of functionality into fewer devices combats the increase in the size and cost of these nodes, making distributed smart sensor systems more feasible.

Many commercially available integrated circuits are integrating greater functionality into single devices. This push to provide greater functionality into a single integrated circuit – the so-called "system on a chip" -- is driven by the need for saving space and lowering cost. A node in a distributed control system must be able to perform several functions:

Measure, often digitize a sensor output

Read the TEDS for transducer data

Output control signals to transducers (often actuators) based on sensor measurements or time, digital or analog

Process transducer data (calibrate, filter, linearize data, "decide" device response based on measurements, etc).

Communicate with an area network system bus (e.g., CAN)

To *measure* the output of a sensor and then send it to a digital network, a signal is sampled with an analog-to-digital converter (ADC). This data can then be stored in digital memory (e.g., RAM) or sent to the system communications bus (CAN). The TEDS information must be downloaded and used by the local processor; usually with digital I/O (this is defined by the IEEE 1451 standard used). This may happen using the 1451.2 TII or another interface as defined in the draft standards IEEE P1451.3 (multi-drop), P1451.4 (mixed-mode interface), and P1451.5 (wireless). Analog and digital output signals to control actuators are needed in distributed control systems. Because smart sensors have local processors, these actuators can perform actions based upon measured inputs. Output control can be digital (e.g., general purpose digital I/O port pin) or analog (e.g., digital-to-analog converters, pulse-width modulation). Additionally, many sensors require an excitation voltage or controlled current input and an analog output device must supply this as well.

Smart sensors typically require some form of *control and processing*. Such processing can be filtering, data correction (linearization, calibration, etc.), closed-loop control, etc.. This is usually performed by an MCU or DSP.

In order to be part of a cohesive network, the node must be able to *communicate* with the other nodes over a communications bus, such as CAN. For this reason, the node should have a network controller. A dedicated protocol controller removes this burden from the local processor. In the case of CAN, a CAN controller will typically manage protocol functions such as filtering messages, handling remote frames, and fault confinement.

If using the IEEE 1451.4 mixed-mode interface, much of this functionality could be integrated. The MMI gives a logical separation that offers a better opportunity to integrate more functionality on the host/network controller side of the interface (the measurement and control device).

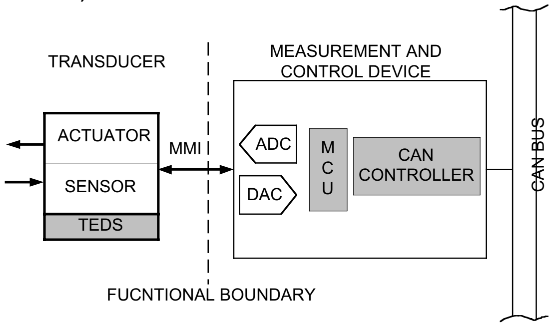

Figure 4. Integration in an IEEE 1451.4 Device

For example, while the transducer contains the sensing elements, actuators, and TEDS, the host processor can integrate the analog functionality (ADC's, DAC's), application and data processing (MCU), programmability (ISP FLASH and EEPROM), and communications (i.e., a CAN controller).

There are many CAN and MCU integrated controllers available that integrate analog functionality that will lower the chip count and size of the design. With fewer devices and the space needed to route signals between them, the circuit board will require much less area – critical in many smart sensor designs. While an MCU with integrated CAN and high quality ADC's and DAC's cost more than an MCU alone, the cost of the integrated solution will be less than utilizing several chips. Also, smaller circuit boards with fewer signals and devices cost less to fabricate. Fewer devices with fewer interfaces also means a more simple and reliable design.

While there are many advantages to integrated solutions, there are some cases where this does not work well. More integration can mean less flexibility, especially if there is not a device that fits the design requirements. For example, if the design requires CAN connectivity, high-throughput digital signal processing, and the resolution of a 24-bit delta-sigma ADC, there may not be an integrated solution that is commercially available. However, there are many solutions that fit smart sensors needs very well. A sensor that requires digitizing with a SAR ADC as low as 8- and up to 16-bit resolution will find many devices available at reasonable cost with integrated CAN controllers. Another potential problem is analog performance. While analog performance specifications are not critical in some designs, many smart sensors need high performance ADC's. Mixed-signal integration is a difficult problem to solve, and many solutions sacrifice ADC performance to do so. However, there are high quality ADC's available in mixed-signal devices, so the designer will want to carefully check the performance specification guarantees before designing with such devices. Lastly, because IEEE 1451 separates the transducer module from the network bus (the transducer can be used on any bus), the network controller should NOT be integrated into the sensor module itself if IEEE 1451 compliant. In some cases, the sensor data is digitized on the transducer module (STIM in 1451.1 and 1451.2), and so the module requires an ADC and a processor. In other interface standards, the functional boundary simplifies the transducer while placing more of the burden on the network and application processor. IEEE 1451.4 allows analog output to the measurement and control device; so more integration can be used on the network side of the node in this case. In short, the functional boundary of the interface standard used will affect the integration strategy.

As more integrated IC solutions with CAN controllers become available at lower cost, transducer nodes in distributed control systems will drop in cost and size. This will facilitate more efficient and sophisticated smart sensor CAN systems.

An IEEE 1451.4 Node With CAN Connectivity

While the STIM and NCAP IEEE 1451.1 and 1451.2 have not yet gained wide acceptance, there are several new promising standards, and some use a more simple approach to smart sensor connectivity. The aforementioned IEEE 1451.4 is such a standard using a mixed-mode interface (MMI) that allows direct analog sensor input and output. The MMI uses the Dallas proprietary 1-wire interface protocol. While the previous TII required the STIM to output digitized data to the NCAP, the MMI accommodates signaling on the analog output of many currently available sensors. To facilitate plug and play capability, the sensor maintains a TEDS in non-volatile memory and the MMI allows two methods of providing access to the TEDS. One method allows the transfer of digital data using the existing sensor analog output wire (class 1).

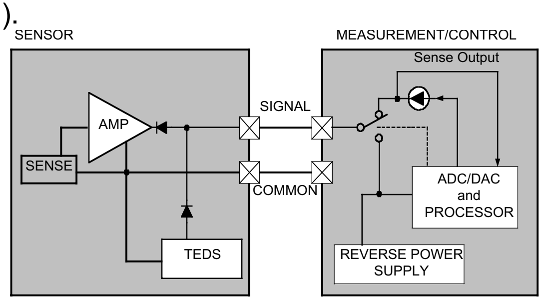

Figure 5. Class 1 Shared Interface

This allows many legacy sensors to be used in smart sensor applications. Another method (class 2) uses a digital only interface separate from any other sensor output. The Class 2 interface also uses the 1-wire protocol, which can be implemented via software and a general purpose digital port pin. The sensor retains the TEDS in on-sensor non-volatile memory, typically EEPROM. An IEEE 1451.4 compliant sensor can have as few as two wire leads, signal and ground.

Because the functional boundary of the sensor module (what was the STIM) and the measurement and control device (what was NCAP) have changed (while maintaining compatibility with 1451.1 and 1451.2), more functional integration is possible when using the IEEE 1451.4. The sensor is only required to provide an analog output and TEDS access. The rest of the node's functions such as digitizing the sensor output (ADC), providing sensor voltage (DAC/PWM), data processing/application (MCU), and bus communications (CAN controller) are performed by the *measurement/control device*. The measurement/control device may include an optional transducer block object. Most of this functionality can be integrated into one device.

As an example, an IEEE 1451.4 bridge-type sensor with CAN connectivity requires:

- Excitation voltage applied to the sensing element
- Amplification and high resolution digitizing of its voltage output, with a voltage reference
- Data processing of the measured signal to relate to measured parameters and calibration
- A method to access the on-sensor TEDS
- Management of CAN protocol tasks, and connection to a CAN small area network bus

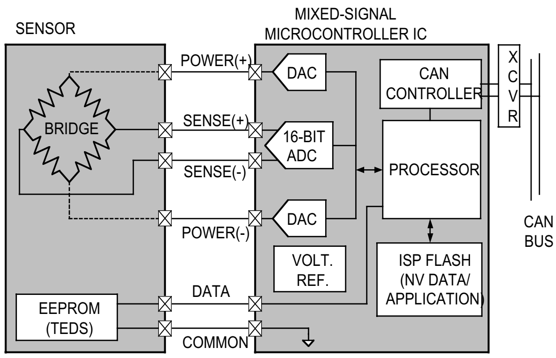

Figure 6. IEEE 1451.4 Bridge Sensor and Integration

Such a transducer node can require several devices in order to implement, especially compared to a traditional "dumb" sensor. However, with the exception of the CAN physical layer interface (i.e., transceiver and isolation), all of the functionality could be implemented into one *device.* Additionally, such devices typically feature in-system programmable FLASH or EEPROM, making the system more flexible (e.g., storing calibration constants, in-system bootloading, updating firmware, etc.)

CONCLUSION

As the demand for greater functionality in real-time control systems increases, the demand for a diverse set of smart sensors for use in these systems will grow.

To make real-time distributed control systems feasible, the cost and size of these nodes and the method in which they communicate must be minimized. To reduce the cost of the new complex transducers and their measurement and control devices, functional integration should be considered. Integrated circuits that combine mixed-signal functionality such as ADC's and DAC's with processor cores (i.e., MCU's and DSP's) are commercially available at reasonable cost. Many of these IC's also integrate communications protocol controllers and in-system programmable FLASH and/or EEPROM. Such integration lowers the size and cost per transducer node and increases reliability.

Controller area network is a communications protocol designed with real-time distributed control networks in mind. CAN offers a mutli-master system of communication along with message priority and error control. High-level protocols written for CAN aid in the implementation of CAN and reduce the time to market. The new time-triggered CAN (TTCAN) offers deterministic communications performance; showing CAN will continue to evolve to be the network of choice in smart sensor systems.

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NOTES:

1. *Serial Peripheral Interface is a trademark of Motorola Corp.*
2. *1-Wire protocol is a registered trademark of Dallas Semiconductor Corp.*

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