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Progress of Smart Sensor and Smart Sensor Networks

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Abstract **- Rapid development of industrial applications imposes more challenges on traditional sensors that only provide raw signal. As a trend, smart sensor and smart sensor network sensors are getting more attention in industrial areas for the values they can bring into the system. One way or another, sensor data will ultimately be used for control purpose. Smart sensor and smart sensor networks will go beyond raw signal and/or data, and provide certain level of information and/or knowledge, which can significantly improve the overall control system perform and reduce reliability. This paper gives a brief introduction on smart sensor and smart sensor networks and their progresses. Some issues observed are also highlighted. By raising people's attention and interests, authors believe that researchers/developers from both academic and industrial societies can and should work together to address those issues and promote the development of smart sensor and smart sensor networks.**

Index Terms - Smart Sensor, Smart Sensor Network, Interface, Fieldbus, Standard

I. Introduction

Sensor market, which is expected to grow to $43 billion by 2008, is very competitive [1]. Industries are biggest sensor users. With the dramatic development of IT technology, industrial applications are evolving dramatically. For example, more information is needed to control the manufacturing quality, reduce unnecessary maintenance, and improve system reliability and other system level functionalities. As a trend, easy-to-use, more connectivity, more self-diagnosis capability, etc., are adding to application users' requirement list. Not only is accurate and reliable sensing signal critical to system, but also other value added enhancements like reduced setup cost, reduced maintenance cost, improved system reliability, are expected to help users' success in tougher competition. The market continuously demands devices, appliances, and systems with better capabilities, enhanced functionalities and easy usage. Sensors, used in these devices and systems to provide information on the parameters being measured or to identify control states, are good candidates for increased build-in intelligence [2].

Smart sensor is emerging to address all those challenges. The term Smart Sensor was introduced into the sensor market around the mid-1980s [3]. Three main factors have coalesced to advance this type of "smart" sensing: decreasing sensor cost, embedded microcontrollers, microprocessors, and analog-to-digital and digital-to-analog converters (ADCs and DACs); the proliferation of networking and diagnostic software; and evoking interface standards that simplify sensor networking. As a result, industry, the government, the military, and businesses are looking to smart sensors and digital communications for more efficient and flexible operations [4]. Fig. 1 illustrates the importance of "smart" sensors over traditional analogue sensors with regard to easy of configuration and connectivity.

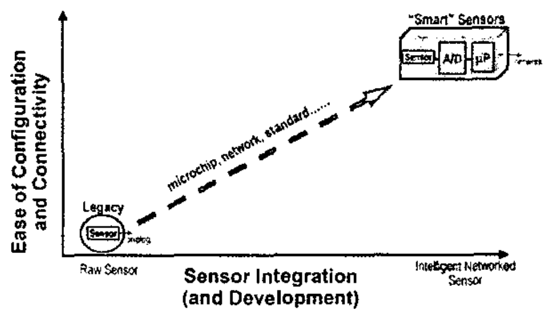

Fig. 1. Smart sensor technology evolution [5]

With the development in technology and market drive, smart sensor and sensor integration become practical and in fact they represent a peak and ongoing trend in industrial applications.

The most basic capability of smart sensors is the ability to communicate in non-analog fashion. So communication interface for a smart sensor is of great importance. The real motivations to interface sensors and networks mainly include, but not limited to:

- Cost saving: Simplified service, operation and maintenance, reduced wiring and rapid start up can be expected. Elimination of large, unwieldy bundles of cables and the associated mess is an obvious advantage.
- Powerful remote monitoring: Better asset management and preventive maintenance can be achieved by remote monitoring. Enterprise information can also be integrated,

which provides improved supervisor/administrative insights.

- Modularity: Connectivity of modules is achieved through software. Taking a large system apart, putting it on a truck, and reassembling it somewhere makes life much easier.
- Flexibility: The ability to accomplish rapid changes to sensors and sensor system makes it possible to adapt to different applications and/or transmit information from/to difficult or inaccessible locations.
- More accurate measurement and efficient coding at higher data rates: With this characteristic, more network capability can be added to the smart sensors, to name a few, remote- and/or self-diagnosis, remote calibration, sensor parameters tuning, etc.

In this paper, smart sensor and smart sensor networks and their progresses are introduced. Issues observed are highlighted. The paper is organized as follows. In Section II, smart sensor is covered. Section III and IV discussed the status and issues of current smart sensor networks. Conclusion is given in Section V.

II. SMART SENSOR

What additional features does a generic dumb sensor have to exhibit to be considered smart? To date, no common agreement has been reached over the definition of smart sensor with the absence of an official definition from any standard-making organization. Some grant the title of smart sensors to devices that communicate digitally, while others are referring it to single-chip sensing mechanisms. Some exclude from this category devices with calibrated output or devices that don't perform actuation and control [6]. IEEE defines a smart sensor as a sensor "that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This function typically simplifies the integration of the transducer into applications in a networked environment" [7]. This definition may provide a starting point for deciding the minimum content of a smart sensor.

The key feature of the smart sensor is the combination of the sensing element (or simply called sensor if no confusion will be caused), information processing and communication technology, which equips the sensors with more advanced functionalities than sensing raw data only. In the next paragraphs, two ways for exploring characteristics of smart sensor, i.e., architecture and functionalities, are discussed respectively.

From the architecture perspective, most definitions of a smart sensor include the basic architectural elements shown in Fig. 2 [8]. This architecture consists of seven major elements:

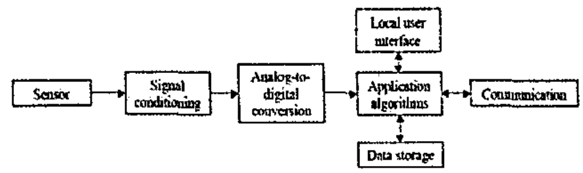

Fig. 2. The basic architectural elements of a smart sensor

- *Sensor:* A device converting energy from one domain into another. The device may be either a sensor or an actuator.
- *Signal conditioning:* Circuitry that prepares the electrical signal for conversion to the digital domain. (Note that some sensors, such as simple presence detectors, limit switches, counters, etc., are inherently digital). To list a few, signal conditioning can include conversion from one form of electrical signal to another (e.g., current- or frequency-to-voltage), amplification, bandwidth limiting through anti-aliasing filters, and more.
- *Analog-to-digital conversion:* A device that converts the analog input signal into a digital code that represents the magnitude of the analog signal. It is generally beneficial to perform this conversion as closely as possible to the point of measurement.
- *Application algorithms:* Application-level software or hardware whose functions include converting the data to user-specified units, signal processing, data analysis and reduction, watching for alarm conditions, logging time-stamped records to memory, running local control loops, or other operations appropriately performed closely to the point of measurement. These algorithms provide the "smartness" in smart sensors.
- *Data storage:* Digital data storage for sensor identification and configuration information, calibration data, user display preferences, the time-stamped logged data, and anything else that is valuable to store within the sensor. As memory and communication bandwidth become more available, it is likely that the entire or part of sensor documentation, including manufacturing and user history, setup procedure and user manuals, can be stored in the sensor where they will not be misplaced.
- *User interface:* A standardized presentation of corrected data to the end user in the user's language and terminology, and in the application-specific physical units.
- *Communication:* An interface to a communication medium for remote access to the sensor for setup, calibration, diagnostics, data capture, and general status monitoring (to name a few). For smart actuators or systems with mixtures of sensors and actuators,

communications can include commands such as updating outputs and changing set points, etc.

From functionalities perspective, additional capabilities need to be provided to translate the dumb sensor into smart one. Based on our study, the authors compiles an attributes' list highlighting smart sensors' capabilities. Importance and/or acceptance of most criteria is user and application specific.

- *Two-way digital communications*: Overwhelmingly, this is the number one parameter, mentioned by nearly everyone [9]. Only when communication is supported, can other important functions be realized. One of the key functions is remote configuration and calibration. Smart sensors need to be scalable, able to be re-configured and/or re-ranged, calibrated, and downloaded with process loop variables. Such communication can be built on simple signal form (e.g., RS-232 or RS-485) or other more sophisticated standard buses like HART, Profibus or FF (Fieldbus Foundation). In some cases, smart sensor is capable of two-way communication in factory configuration while in operation just send data back for reliability consideration.
- *Self-identification*: The smart sensor must know what it is and how it works, and it should communicate that information with other components via a network. This is accomplished by providing the capability to embed key sensor information and its performance in a standardized format using a small amount of nonvolatile memory. This feature enables the automation of diagnosis, configuration, and identification procedures in a multi-vendor sensor (component) environment. Furthermore, when sensors can identity themselves and their capabilities to a system, plug-and-play will become feasible.
- *Self-diagnosis*: The great thing about a smart sensor is that one may not have to send a maintenance person out in a driving rainstorm in the middle of the night to check an instrument on top of a distillation tower when a problem is suspected. Instead, a suitable HMI display can be just called up from the comfortable control room and run a remote diagnosis at all times. With self-diagnosis capability, the smart sensor can indicate if it is malfunctioning, or if something is about to go wrong. Such diagnosis covers sensing element, electronics, loop power supply, wiring, meter body, etc [9].
- *More powerful data processing*: Today's inexpensive, small microprocessors are increasingly making their way onto sensors. Providing powerful measuring and computing capabilities may equip sensors with advanced algorithms to translate input raw data into information and then knowledge, e.g., auto-calibration, self-correction, compensation, etc. In addition, triggering, status, and control information and corresponding data operation should be provided to support proper functioning of the sensors.

With the technology development, many advantages of the smart sensors are represented in the continuous positive growth of smart sensors market. To list a few, below are some of the benefits:

- *Easy/faster installation and maintenance*: With self-identification capability, smart sensors can be easily installed into a measurement / control system in a Plug&Play way, which eliminates traditional paper work. System setup will be more automated and will incur less opportunity for errors. It will also improve sensor data management, bookkeeping, and inventory management.
- *Increased diagnosis and advanced functionalities:* Other advantages of smart sensors include, but not limited to, the increased diagnosis at the sensor level and their added advanced functionalities in collected data manipulation. In other words, smart sensors are able to immediately identify and report any malfunction of a system or plant machine. With the ability to amplify and digitize signals, unexpected downtime is thus minimized, and the overall system reliability is improved. . The flexibility of equipping sensors with the calculating compatibility of microprocessors and other electronic devices takes smart sensing beyond the scope of a narrowly defined instrumentality.

In current competitive market, sensor manufactures are under pressure to apply new technologies to build low-cost smart sensors that meet the continuous demand of versatile sensor application. Making sensors networked or integrated into systems has been an active area of smart sensor development and application. With this consideration in mind, following sections will be devoted to the networked smart sensor and sensor fildbus technology, respectively. According to Frost & Sullivan's North American Smart sensors market study, in 1998 revenues totaled $259.5 million with a growth rate of 4.0% and it was expected that by 2001 this market reached revenues of $287.9 million, as illustrated in Fig. 3, at a compound growth rate of 3.8% [10].

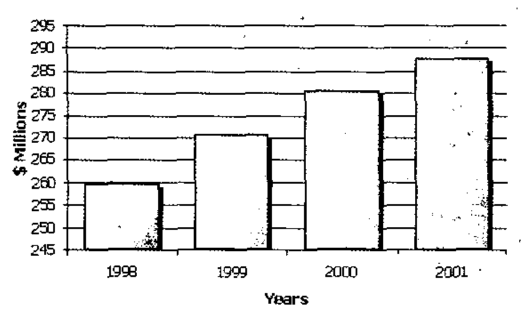

Fig. 3: Total smart sensors market in North America, 1998-2001

Now there are several application markets starting to incorporate smart sensors into their systems. From consumer electronics and automotive to process control industries, smart sensors are starting to be the instruments of choice for these applications. As mentioned earlier, these sensors' self-diagnosis nature and their high level reliability make them very attractive to plant managers and engineers. Table 1 illustrates the percent of revenues of some of the most potential end-user segments for the North American smart sensors market. The process control industry is the largest end-user group accounting for 22.2% of the total smart sensor market as of 2000, which was the same in 1998. Over the past decade, a variety of companies have created HART protocol compliant devices. These devices provide a powerful bridge between the analog and digital worlds. Briefly, the HART protocol is the current, most common method of communication used in smart process instrumentation.

The rapid development of not only the sensor industry but the end-user markets like the automotive, electronic, HVAC, and process control sectors is expected to boost the growth of smart sensors markets in future years.

Table 1: Revenues by End user in North America, 1997-2000

Year	P.C. (%)	P.G. (%)	T&M (%)	HVAC (%)	Elect. (%)	Auto (%)
1997	22.6	19.7	15.5	8.3	5.6	4.3
1998	22.2	19.4	15.3	8.4	5.9	4.1
1999	21.8	19.5	15.1	8.5	6.2	4.2
2000	22.2	19.5	15.1	8.6	5.5	4.4

Key:
P.C. = Process Control
P.G.= Power Generation
T&M = Test & Measurement
HVAC = Heating, Ventilating and Air Conditioning
Elect.= Electronics
Auto = Automotive

III. Smart Sensor Networks

Smart sensor devices may not be the panacea as early proponents have suggested (further explanation in the next section). Other technologies, such as smart sensor interfaces, may provide essential tools to help make industrial processes more efficient and better integrate manufacturing operations with the rest of the enterprise [11]. Smart sensor network is becoming the approach of choice, particularly in the industrial area, where many legacy and what some would call "dumb" sensors predominate. Here, industry wants to exploit the operational cost and efficiency savings it can gain by networking its sensors to become more intelligent over a larger system scale.

A. Networked Sensor Based on Fieldbus Technology

Nowadays, a number of different mostly incompatible fieldbus solutions for smart sensor networking have been developed and promoted. The evolution of sensor networks has been fuelled by technological innovations from the sensing, computer, and communications areas. The growth of these networks has accelerated to meet demands for sensor usage in a wider range of applications and for enterprise-wide information exchange. As these technologies being incorporated into sensor networks, three clear generations have developed, shown in Fig. 4 [12; 13]. The development is discussed below.

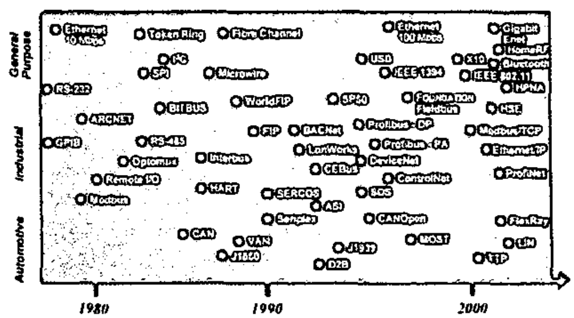

Fig. 4. Chronology of key sensor networks

- *From the point to direct link*: The first generation of sensor network technology was point-to-point. Interface standards such as current loops and the 1~5V signal provide a way for sensing and control information to leave and reach sensors and actuator. The sensors' and/or actuators' analog signal provides a single dimension of measurement.

- *From direct link to network*: The second generation of sensor networking technology was triggered by the development of the microprocessor, which allowed computation capability to be integrated with raw sensors. Increased intelligence in the node brought up the attention that communication was becoming a bottleneck. The development of such digital standards as RS-232, RS-422, and RS-485 spurred the creation of numerous simple sensor networking schemes. Some of them, including Modbus, are still widely used today.

- *From simple network to system*: Technology improvement behind the third and current generation of sensor networking technology came out of the development of the Manufacturing Automation Protocol (MAP). MAP was designed to reduce the cost of integrating various networking schemes into a plan-wide system. The result was the development of the Manufacturing Messaging Specification (MMS).

Align with the network developments, more than 60 different sensor network protocols geared for a broad spectrum of industries, providing various degree of functionality and success for different requirement. Authors made a list of popular sensor buses or networks in use today:

- *ASI*: "Actuator Sensor Interface", was developed in Germany by a consortium of sensor suppliers. A low-cost, bit-level system, designed to handle 4 bits per message for binary devices in a master/slave structure operating in distance up to 100 meters. It is designed mainly for factory automation and process control environment.
- *HART*: "Highway Addressable Remote Transducer", is a network promoted by Rosemount Inc., which provides two-way digital communication atop traditional 4mA~20mA loops at the rate of 1200 bps. Utilization of continuous analog signal as the primary process signal makes it well suited for continuous and batch control applications. And for many users with legacy control systems and have difficulty in justifying holistic retrofits or migrations to newer all-digital technologies, HART is a simple yet effective solution. It is still popular in sensor network market.
- *FF*: "Foundation Fieldbus", was formed from the merging of components of specifications by WorldFIP and Profibus supporters to test and demonstrate fieldbus components to support an eventual single, universal fieldbus standard. However, only 250,000 FF-enabled instruments are currently in use, despite the fact that FF technology has been available for around five years. The technology of FF has yet to demonstrate enough value for wider user acceptance.
- *Profibus*: "Process Field Bus", was developed in Germany and strongly supported by Siemens. It is German DIN Standard 19245. It consists of 4 parts. Part 1&2 are designed as Profibus-FMS and cover automation applications in general. Part 3, Profibus-DP, is a faster system for factory automation applications. Part 4, Profibus-PA, is in preparation for process control applications.
- *CAN Bus*: "Control Area Network", was developed in Germany by Robert Bosch GmbH with Intel and Philips in the early '80s for automotive in-vehicle networking. Selectable baud rated up 1 Mbps, and twisted pair, fiber, coax, and RF media is supported. CAN is ISO Standard 11898, approved for passenger vehicle applications. CAN-based systems were approved by SAE as Standard J1850 for American passenger cars and Standard J1939 for trucks and large vehicles.
- *DeviceNet*: An application protocol built on top of CAN, developed by Allen-Bradley. It features the use of object-oriented software and is used primarily in industrial control systems. It uses a 4-wire (signal pair and power pair) shielded cable and can support up to 64 nodes per network segment at speeds up 500Kbps at 100m or 125Kbps at 500m. An Open DeviceNet Vendors Association (ODVA) has been formed.
- *Industrial Ethernet*: Industrial Ethernet has become a byword for forward thinking industrial networking in the 21st century. Many industrial fieldbus vendors are encapsulating existing protocols in TCP/IP. Presently there are four major contenders: Modbus/TCP (Modbus protocol on TCP/IP), EtherNet/IP (the ControlNet and DeviceNet objects on TCP/IP), Foundation Fieldbus High-speed Ethernet, and ProfiNet (Profibus on Ethernet).

These instrumentation protocols have emerged as standards for connecting sensors, discrete and analog I/O, and smart devices to Ethernet. A study by the ARC Advisory Group predicted that use of Ethernet in such applications would increase by 84% in the next two to three years. The study also concluded that use of Ethernet in factory floor I/O rose 54% between 2000 and 2002. Though still there are some issues that must be addressed for Ethernet to become a viable, popular and plant-floor fieldbus, its move to the factory floor is inevitable because Ethernet offers far more bandwidth than such proprietary I/O networks as DeviceNet and Profibus, and more communication connectivity between manufacturing operations and front offices, which have employed Ethernet for many years [14].

Table 2 summarizes characteristics of various buses.

Table 2: Fieldbus Summary

Fieldbus	Master	Max Segment Length	Max Speed	Wire	Max Stations	Standard
ASI	single	100m	167kb/s	2	32	EN50295
BITBUS	multi	300m/375kb/s	375kb/s	2	251	IEEE1118
		500m/125kb/s				ISO11898
CAN	multi	40m/1Mb/s	1Mb/s	2	64	ISO11519
		5km				open
ControlNet	multi	250m/48 nodes	5Mb/s	coax	99	specified
		500m/125kb/s				open
DeviceNet	multi	100m/500kb/s	500kb/s	4	64	specified
		2000m				open
Foundation Fieldbus	multi	9.5km total	31.25kb/s	2	240	specified
FIP	multi	2000m/1Mb/s	2.5Mb/s	2	256	EN50170
INTERBUS	single	12.8km	500kb/s	8	255	EN50253
LON	multi	6.1km/5kb/s	1.2Mb/s	2	2	ANSI
Modbus plus	multi	1.8km	1Mb/s	2	32	proprietary
		19.2km/9.6kb/s				
PROFIBUS FMS	multi	200m/500kb/s	500kb/s	2	127	EN50170
PROFIBUS DP	multi	1km/12Mb/s (4 repeater)	12Mb/s	2	127	EN50170
PROFIBUS PA	single	1.9km	93.75kb/s	2	32	EN50170
Seriplex	single	1000 feet	~250kb/s	4	510	proprietary

B. Effort to Standardize the Fieldbus

A smart sensor interface should conform to a worldwide standard. Such a standard for a real-time communication has been long sought, but efforts to get consensus on one agreed standard have been hampered by vendors, who have been reluctant to support such a single common standard in fear of losing some of their competitive advantages. Also suppliers want to promote their own proprietary standards by making some modifications to make them "open". This only results in multiple standards, each with its own characteristics, and not "inter-operable" with each other. The industrial automation network standard has been a subject of committee deliberations for a long time. Some of the existing proposals have been combined and standardized:

- In 1994, two large rival fieldbus groups, ISP (Interoperable Systems Project supported by Fisher-Rosemount, Siemens, Yokogawa, and others) and the WorldFIP (supported by Honeywell, Bailey and others), merged to form the Fieldbus Foundation (FF). The objective of the FF is to develop a single interoperable fieldbus standard in cooperation with the International Electrotechnical Commission (IEC) and Instrumentation Society of America (ISA).
- The IEC worked out the IEC61158 standard. It is based on eight existing fieldbus solutions. However, the IEC fieldbus draft standard was not ratified at the final approval vote, following a set of controversies. The IEC61158 has the big disadvantage that it still keeps a diversity of eight different solutions and it is not really an "open" standard.
- The ISA, which developed the SP50 standard and IEC committees met jointly to make the development of an international standard possible. ISA SP50 was the same committee that introduced the 4-20 mA standard back in the 1970s.

To date, however, these efforts on standardizing different fielbus practice have not achieved what they want. End-users continue to be confused - waiting for the standard that never comes, or working with their choices of one of the several, fairly good, proprietary, "open" networks.

IV. Issues Existing in Smart Sensor and Smart Network Areas

Given the advantage the smart sensor, the networked compatible smart sensors have yet to be widely used. According the recent statistics carried out by ARC Advisory Group (http://www.arcweb.com/), the majority of installed field devices, including sensors, are not smart, even though this technology has been around for about two decades. Fig. 5 [15] shows that smart sensors have not been widely accepted in the market.

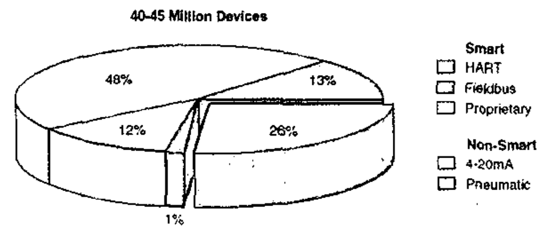

Fig. 5. Worldwide installed base sensor distribution [15]

This means that the technology of smart sensor is still in an infant stage. The restraints in smart sensors market (North America, 2001-2007) are listed in Table 3 [16].

One reason is that fragmented nature of the fieldbus market and the unwillingness or inability of transducer manufacturers to support all the networks in current use. Many sensor network or fieldbus implementations are available, each with its own strengths and weaknesses for a specific class of applications. Lack of approved standard interface for smart sensor networking is a serious challenge for sensor manufacturers and integrators to interface sensors with all these control networks. Supporting the wide variety of communications protocols represents a significant and costly effort to manufacturers and system integrators.

Table 3: Sensor Market Restrains

Rank	Restraint	1-2 Years	3-4 Years	5-7 Years
1	Absence of universal interface standards limits market growth.	High	High	Medium
2	New smart technology hinders market penetration.	High	Medium	Medium
3	High prices thwart market revenues.	High	Medium	Medium
4	Slow end user acceptance restrains smart sensors revenues.	High	Medium	Medium
5	Skepticism to adopt digital signal conditioning retards market expansion.	High	Medium	Medium
6	Smart I/O distributed systems retards smart sensors growth.	Medium	Medium	Low
7	United States economic slowdown impedes market growth.	Medium	Medium	Low

In addition, smart sensors are currently twice the price of traditional, analog sensors and these high prices are due to the specialized components used in their design. Despite the added benefits of smart sensors, end users will remain reluctant to use them until prices become more reasonable. There are quite many manufacturers that do not have the sufficient infrastructure to immediately convert to a more digitized technology and also lack of compatibility with existing plant process control systems and wiring. Manufactures must develop proper products to increase market share and broaden their customer base according to market drivers.

Recent industry efforts have been focusing on the definition, functionality, and communication standards for smart sensors. The goal is interoperability in a wide range of applications. A pragmatic and modest approach to bring together these disparate views is coming via the adoption of interface standards, spearheaded by the IEEE 1451 Committee [17]. The Committee attempts to bring order to the fragmented world of smart sensing. Attention needs to be paid to the progress of this standard.

V. CONCLUSIONS

Smart sensor and smart sensor networks are becoming a trend in industrial applications. The rapid development of information technology and continually decline of electronics hardware cost will gradually eliminate technology and implementation barriers. The advance of sensor smartness and the connectivity will bring more benefit to application and users, to name a few, overall system reliability, auto re-range, remote diagnosis, etc. Academic and industrial researchers/developers can and should work together to resolve the issues currently existing and promote such development.

Authors have been following the progress of different societies (including IEEE 1451) and working to resolve above-mentioned issues. In Fig. 6, a high-level smart sensor architecture with adaptive sensor network interface is proposed. Next step is to fully implement and evaluate such architecture and have the tradeoff over functionalities, flexibility and cost for different applications.

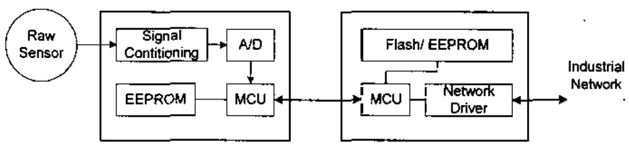

Fig. 6. Proposed smart sensor architecture as next step's study

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