PROCESS CONTROL INSTRUMENTATION: STATE OF THE ART AND FUTURE TRENDS

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ABSTRACT

In modern industrial installations, instrumentation represents an important and crucial part for the efficient operation of industrial processes. Instrumentation is used for measurement, monitoring, and control of the plant. Due to high complexity of new installations, requirements for higher safety and demand for high profit, instrumentation technology in industrial processes is taking a new trend at the turn of the century. This includes Artificial Intelligence techniques, new software, smart transmitter, field bus, networking, predictive maintenance, sensor fusion, etc. The authors will present an overview of the state of the art in control instrumentation technologies in modern industrial installations. Projections for future and emerging process control instrumentation technologies will be highlighted. Emphasis in this work will be given to recently emerging and rapidly developing technologies in the following areas : **Sensor technologies. Field Bus and networking, Software, visualizatison, and multimedia, Artificial intelligence techniques, and Sensor Fusion and applications.**

1. INTRODUCTION

The technological advances that have taken place in microelectronics, telecommunication and computer technologies have revolutionized the instrumentation used for measurement and control in today's industries. With the tremendous size of the market in the industrial measurement and control sector , the momentum given by the advances in electronics and communications is even more felt in this sector than in many other sectors. The impact of all these factors is to make the field of instrumentation for measurement and control ever more interdisciplinary and with endless challenges thrown open especially by the developments in microelectronics , computer software and the ever-increasing demand of industrial processes.

In this paper, we give a tutorial introduction to the largely interdisciplinary field of instrumentation that is relevant for measurement and control. Current practice as well as some future trends, especially in view of the development, cited above, are outlined. We will be concerned with the applications in the continuous process industries such as refineries, chemicals, power and other industries. In continuous process industries the primary concern is with the measurement and control of process variables , such as, pressure, flow, level, and temperature. We give a brief account of the measurement techniques for each of these variables and wherever appropriate, indicate the impact of the advancement of technologies concerned. This is followed by an account of some recent developments in the field bus and networking technologies, software and visualization, Intelligent systems, and sensor fusion. Process control instrumentation technology has seen development in a very high pace as sgown below.

TABLE 1.1 Evolution events in modern instrumentation technology

Year	Event
1900 - 1908	Manual control with gauges and valves
1910 - 1920	Large case instruments in the field
1920-1940	Pneumatic signal & instruments
1945	ISA (Instrument Society of America) was founded
1947	Invention of Transistor at AT&T Bell lab
1948	First Pneumatic differential pressure Transmitter (Foxboro).

1948	National Bureau of Standards(NBS) developed a differential manometer to compare pressure of gases, organic vabors, and non-corrosive liquids.
1950's	Development of central control rooms.
1951	UNIVAC, the first automatic control computer
1952	A.T.James and A.J.P. Martin developed the process of gas Chromatography.
1954	Electromagnetic flowmeters (Foxboro).
1954	DIGITAC process control computer (Hughes Aircrafts).
1955	Ultrasonic flowmeters.
1956	First commercial gas chromatograph (Beckman Instruments).
1957	Ultrasonic level sensors.
1959	4 to 20 mA analog transmission (Honeywell).
1959	All Solid-state controller (Baily meters Co.).
1959	Discovery of superconductivity (Westinghouse).
1960's	DDC Direct digital Control. Introduction of Programmable Logic Controllers PLs (General Motor).
1964	IBM mainframe system/360
1965	PDP-8 minicomputer (Digital Equipment Corporation).
1970's	minicomputers, PLCs, and Networking.
1974	Remote sensing satellite.
1974	MOS technology (RCA).
1975	Fiber optics.
1976	Interactive digital display
1977	First redundant computer configuration.
1977	DCS Distributed Control systems.
1981	Interactive color graphics work station (US-DATA)
1980's	Expert systems, Neural Networks, and Artificial Intelligence.
1981	IBM Personal Computer
1986	MAP Network Manufacture Automation Protocol. CIM Computer Integrated Manufacturing.
1987	First AI controller (Foxboro), HART protocol, and microsensors.
1990's	Smart transmitters, Fieldbus, digital transmission, networking, 3D Windows user interface. Autotuning, Fuzzy controllers
1991-1995	InTouch interactive human interface(Wonderware). Open Architecture. MES (Manufacture Execution Systems). Powerful microprocessors, RISC Chips, Pentium, Alpha, and PowerPC.
1995	SP88 Batch control standard, Windows NT, OLE, OPC (Object oriented Process Control)
1997+	Field Bus Standard, Internet instrumentation.

2. SENSOR TECHNOLOGY

Measured Process variable	Measuring device	Comments	New development
Temperature	Thermocouples] Resistance thermometers] Filled-system thermometers Bimetal thermometers Radiation pyrometers Oscillating quartz crystal	Most common for relatively low temperature	• Noble metal thermocouple to very high temperature s, R, B • IR radiate thermometers • 2nd muldicator IR.
Pressure	Manometers Bourdon-tube elements] Bellows elements] Diaphragm elements] Strain gages] Piezoelectric elements	With floats or displacers Based on the elastic deformation of materials Used to convert pressure to electrical signal	• Piezo-ristance sensor reputably high expearity and accuracy. • Electroceptic pressure trasduces • Vibrating wire and vibrates tube sensors.
Flow	Office plates] Venturi flow nozzle] Dahl flow tube] Kennison flow nozzle] Turbine flow meters Ultrasound Hot-wire anemometry	Measuring pressure drop across a flow constriction For high precision	• Magnetic flow meters • Vortex flow meter • Wioltes mass flow meters • Doppler flow meters • Paddle wheel sensor digital
Liquid level	Float-actuated devices] Displacer devices] Liquid head pressure devices Conductivity measurement] Dielectric measurement] Sonic resonance	Coupled with various types of indicators and signal converters Good for systems with two phases	• Back pressure in bubble tube • Microwave accuracy to 2.5 wi. • Nuclear & rays absorption • Ladles and strain gages • Solid state men sensors.

Intelligent Transmitters (Smart)

Smart transmitters are built on the traditional 4-20 mA current loop transmitters, by communicating with digital signals. Smart transmitters allow many remote functionalities and also output signals for use in the control of the process. In this way, the smart transmitter becomes the localized real-world interface for a remotely located computer. An intelligent transmitter can be functionally defined as one that can communicate intelligently with its peers, analyze incoming data, and make control decisions on its own with or without the supervision of an higher authority. The intelligent transmitter, in other words, can react to stimuli and control the process in real-time. The smart transmitter, however, must wait to control the process until it receives instructions from a remote host. Recent introduction of Intelligent transmitters include such features as, field programmable controller, digital interfaces, digital to analog and analog to digital converters, and a variety of signal conditioning capabilities. The transmitter can function either as a standalone unit or as part of a distributed control system

User Benefits

- provide multiple protocols. These allow for a selection between Analog (4-20 made), a Digital version which is either HART, other proprietary digital protocol, or the FieldBus.

- ♦ Multiple ranges (up to three ranges) that have been condensed so that fewer models are required to accommodate the various spans required.
- ♦ multi-measurements (up to 3 variables) which is a real plus for the users who need that extra temperature or pressure variable that now comes in as a bonus along with the primary variable. on-board diagnostics that provide so much good information that the control system is able to off-load any analysis to the field device and receive real-time data about the health of the unit.

Smart actuators / positioners
(sometimes called digital valve controllers) with non-contacting position feedback. This movement is taking the original analog positioner (with its fixed, "high gain") and creating a flexible, fast and accurate controller to position the valve. They may be applied to rising stem or rotary valves. Their diagnostic features will save users big bucks by giving information on the valve while it is still installed. diagnostics can pinpoint a developing problem before it interferes with process control. Specific areas include packing friction, breakaway torque, stroking distance, proper seating of the plug, nonlinearity, hysteresis, etc. Leak detection for (EPA) fugitive emission is usually a standard offering from the analysis of the trim and packing.

3. FILED BUS AND NETWORK TECHNOLOGY

One of the most anticipated changes in the process control industry has been the introduction of fieldbus. The digital field bus is the recent ultimate of the evolution which has been taking place in the signal transmission technology over the last 5 decades. Ten years in development, fieldbus has been long awaited by many process control industry users. In March 1996, the Fieldbus Foundation released the low-speed (HI) fieldbus technology. With this release, a fully functional fieldbus is defined.

The Fieldbus Foundation was formed from the merger of ISA/SP50 and WorldFIP North America in October, 1994, and has since grown to over 100 companies.

FOUNDATION" fieldbus is a digital, two-way communication link among intelligent field-level and control devices that will replace the 4-20 mA standard. Fieldbus is both open and interoperable, and it is an enabling technology that allows migration of control fimctions to field devices.

Foundation fieldbus has also tackled the tougher issues such as intrinsic safety, hazardous areas, volatile process, and tough regulatory environments. Foundation fieldbus was developed using ISA and IEC standards, and has been specifically designed to provide solutions to meet requirements of the toughest automation environments. No other digital protocol has met these stringent needs.

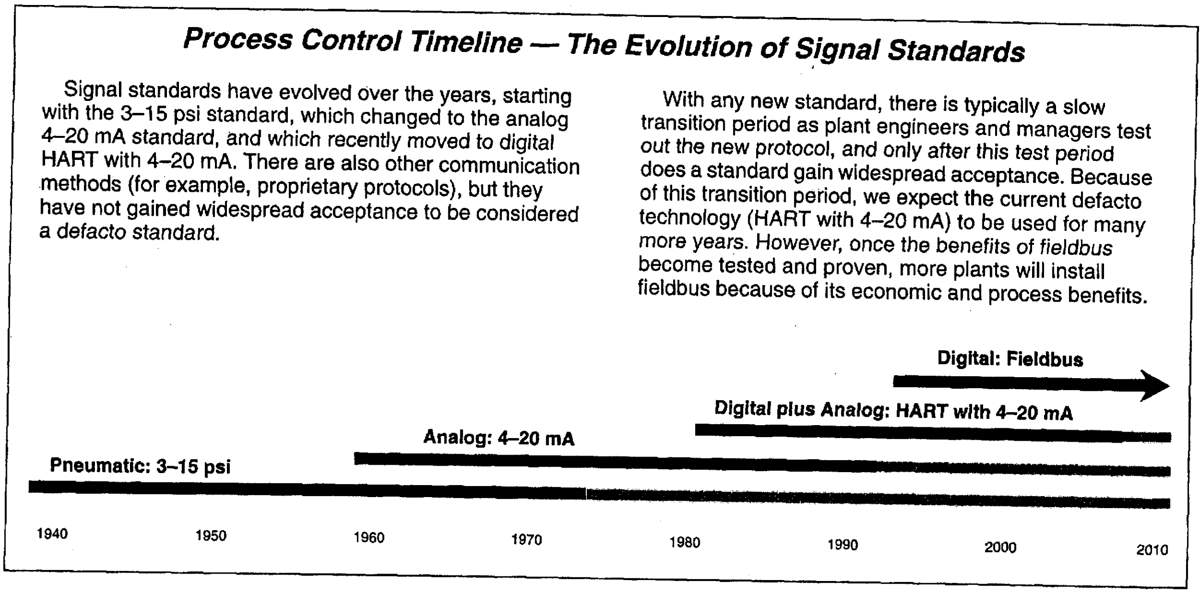

Fig. 1 Evolution of signal transmission technology

User Benefits

- Advanced functions added to field instruments
- Reduced wiring and installation costs
- Reduced I/O equipment requirements
- Improves Maintenance
- Increased process and non-process information
- Quick on-line diagnostics
- Predictive maintenance and audit trail

Table 1 provides examples of other Digital buses and their intended domain of applications. A summary of the main features of these digital buses is presented in Table 2.

The Fieldbus standard defines the base bus H1 to operate at 31.25 kbps. The H2 Release adds the high-speed bus capability (1 MB/s and 2.5 MB/s) to the Foundation fieldbus. This release includes open redundancy capabilities and bridging options. It is important to know that the fieldbus communications protocol remains the same. H2 is an addition to the fieldbus technology, and it will not change devices or control systems that were defined and developed using the HI release tools. A hierarchy of fieldbus networks is depicted in Figure 2. Figure 3 illustrates the fieldbus communication layers as defined in the standard.

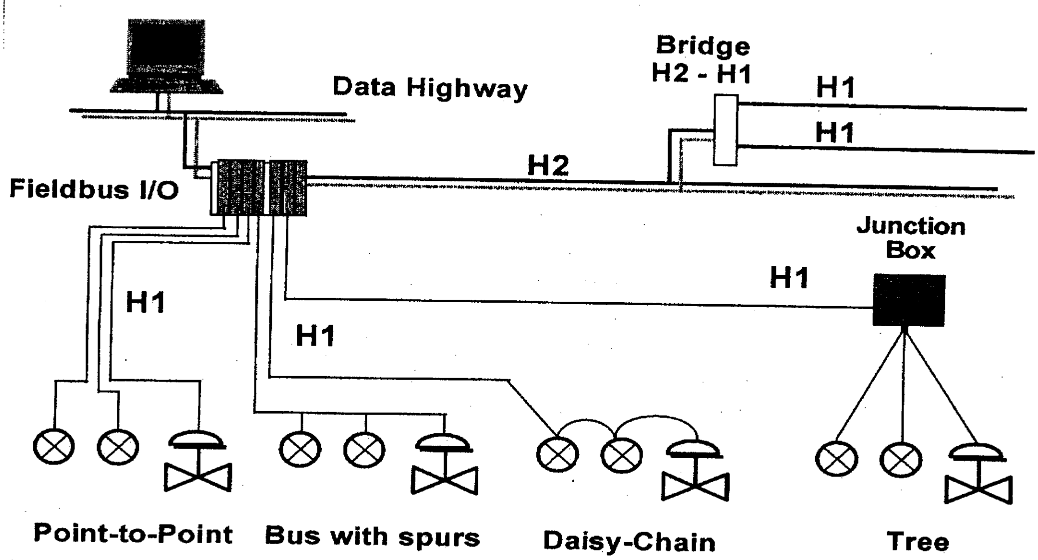

Fig. 2. Fieldbus Networking

Table 1. APPLICATION LEVEL OF DIGITAL BUSES

Fieldbus (H-1)	LonWorks	DeviceNet	SensorBus
Flowmeters	HVAC	Photoelectric	Encoders
Controllers	Lighting	Variable speed	Servo drives
Drives	Security	Motor starters	Proximity switch
Valve actuators	Energy monitoring	Bar code read	Limit switch
Pressure trans.	Fire safety	Microdrives	Safety switch
Process analyzers	Gas concentration	UPS	Pushbutton
Bar code scanners	Occupancy sensor	Positioner valve	Solenoid
,Vision	Heat pumps	Thermocouple	1 Paint co

Table 2. Key Features of Digital Buses

Bus	*Speed Distance*	*Protocol*	*Peer-Peer*	
Fieldbus (H-1)	31.25 Kbs	1900 M	Deterministic	Yes
Fieldbus (H-2)	2.5 Mbs	750 M	Deterministic	Yes
thernet	10 Mbs		CSMA/CD	
Fast Ethernet	100 Mbs		CSMA/CD	
Lon Works	1.2 Mbs	2000 M	CSMA/CD	Yes
ControlNet	5 Mbs		Deterministic	
Profibus PA	12 Mbs	1200 M	Deterministic	Master/Slave
Profibus FMS	12 Mbs	1200 M	Deterministic	Master/Slave
World FIP	2.5 Mbs	2000 M	Deterministic	Master/Slave
HART	11.2 Kbs	13000 M	1 FSK	Yes

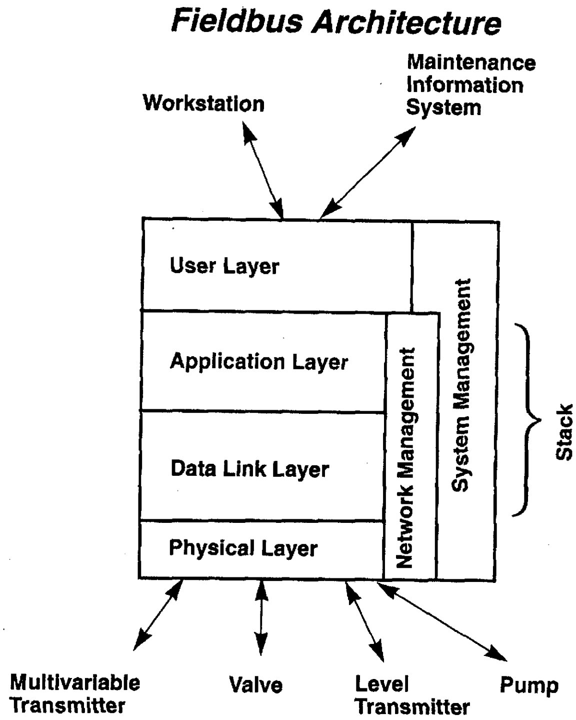

Fig. 3. Fieldbus Layer

Local Area Networks

A quick review of the available buses start with the *LAN (local area networks)* that support the backbone of the system and should not be confused in any way with field based buses. These buses are usually the proprietary backbones to a DCS or they option for TCP/IP over Ethernet or maybe FDDI. These high band width networks not only connect to sprawling control systems but provide a conduit to the world of IT (information technology) or the Enterprise Intranet for integration to the business world of the corporation. The basic topologies of IEEE-802.5 (token-passing ring developed by IBM), IEE-802.4 (token-passing bus and MAP) and IEE-802.3 (CSMA/CD, carrier sense multiple access with collision detection called Ethernet and developed by Xerox) are still the basis for many of the protocols that connect the workstations and computers together. The changes come in the form of the protocols that utilize these topologies such as SNA by IBM, DECnet, FDDI and now ATM for the business world. The control layer typically uses TCP/IP and other proprietary protocols running over Ethernet. The current favorite seems to be Fast Ethernet, 10OBase-T and ATM that provide bandwidths of 10OMbps and 155Mbps respectively. In the environmental industry the HVAC suppliers use BACnet (building automation network) and ARCnet (the oldest commercial LAN) as their weapons of choice. With the incorporation of the Internet and Intranets into the control world, Java and COBRA have teamed up on one

ATM is a switch system instead of a bus. Every station on the system talks first to a switch that has intelligence through the backplane or through the CPU of the switch to logically connect to another line. 'Me ability for every line segment to operate at a different speed , if necessary, is built into this kind of bridging function. The conununication channel is established at, the sessions layer of the protocol. A negotiation is done for connection so that the routing is built right into the network. The idea is not to waste many data bits as overhead.

Today, the interconnected network of computers which we call the Internet has changed forever the way we research information, check a weather forecast, scan today's news, read a book, send e-mail to a colleague on the other side of the globe, join a chat group and share in "discussions" on topics of mutual interest, review recent articles about personal computers in control, learn about the newest analytical instrumentation, access global bulletin boards, visit an electronic bookstore, request literature about a new piece of hardware, even order it if you wish, and on an on.

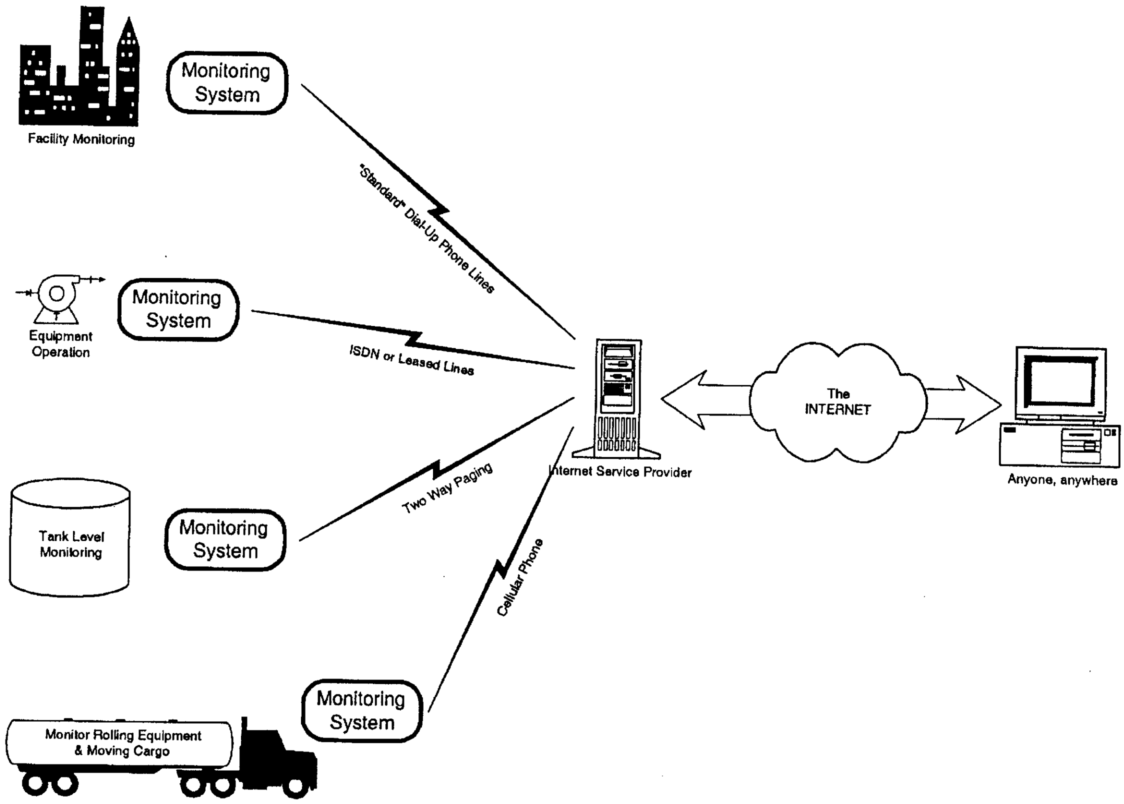

Figure 4 illustrates a typical application of internet in the process industry.

4. VISULALIZATION AND SOFTWARE

The main milestones of the recent developments in the instrumentation software and Man-machine interface MMI can be summarized as follows

1- Windows environment which enables the user to run and interact with several applications simultaneously and to use icons and cursor movements for selection and navigation theory and access applications.

2- Object oriented programming and OLE. The OOP approach structures programs into logical function modules that can be grouped into hierarchical classes based on their common features. A function unit is dealt with as an object encapsulating its data and its manipulating functions or logic. The OLE (object linking and embedding) is a set of system services that provides a means for applications to interact and interoperate. The OLE enables integration of functions and data from standard applications to create new applications.

3- ActiveX controls. ActiveX control technology is a Microsoft standard for code interchangeability and integration under windows 95, 98 and NT. ActiveX controls deliver an easy-to-use property page interface for configuration; flexible events and methods for programmatic control.

4- Virtual Instruments. The operator interacts with color graphics that mimic instrument front panels. The operator can tailor his display by placing his controls data by choosing objects from gauges, control pallets, buttons, knobs, meters, numeric displays, recorders, charts, switches, slides, LEDs, etc.

5- Plug and Play is a specification prepared by Microsoft, Intel, and other PC-related companies that will result in PCs with plug-in boards that can be fully configured in software, without jumbers or switches on boards.
6- visual programming or graphical programming the engineer creates his programs using mouse drag and drop techniques from a graphical menu containing function blocks. The engineers and scientists assemble their block diagram in an intuitively an in high level functionality rather than concentration on language code and syntax.
7- Multimedia technology enables the integration of pictures, video, sound, and text in the operator interface. Multimedia Scene-based Interface, based on plant images and video, enables the operator to monitor and control plant conditions in relation with site images.
8- Client-Server applications
9- 3D process graphics, animation, and virtual reality. The 3D graphics revolutionizes the concepts of process graphics. The operator display now includes 3D graphics of the process units, and animation which illustrates the product flow and the various operating states of the processes. Virtual reality relies on a computer model of the environment which may also integrate actual scenes from the plant. Such technology enables operators and supervisors to navigate through the plant and creates scenes appropriates for examination and inspection of various parts of the plant.
10- Internet. Internet provides several new and unique methods for communicating with equipment at remote sites to provide new service capabilities, improved cost saving and effective alternatives to traditional RF and leased-line telemetry systems. Internet provides access to information data banks, worldwide connectivity to expertise and consultations with peers on other sites.

5. Artificial intelligence, soft sensors, and sensor fusion

5.1 Artificial Intelligence

Many of the chemical processes are critical enough to require constant monitoring and supervision. High risks and costly repairs result from products which are produced out of tolerance. This points to the need for specialized operator expertise being available continuously and especially during emergency troubleshooting procedures. In such circumstances when the human expert is not available, an expert system incorporating the knowledge of the experienced operators of the plant, can assure around-the-clock access to the required expertise.
In effect, a model of the plant concerned is developed off-line initially. As it evolves the expert system incorporates an application which infers in real-time The system is based on known plant tendencies. pattern matching and measured data. The system can forecast operating deviations a few hours in advance. If corrective action could be taken within the advance warning period, the plant performance could be effectively improved through reduced deviations from the operating points and a more consistent product results. It has been estimated, in one particular application, that an off-line diagnostic expert system would solve about 35 % of the deviations in the plant. This figure could rise to as much as 75% in that particular application if the system could actually forecast some of the deviations in advance. The forecasting system was made possible through an on-line real time expert system. The tremendous interest in the knowledge-based intelligent techniques has given a new momentum to the field of instrumentation and measurement. The knowledge-based intelligent techniques have been applied successfully in the design and diagnosis of instrumentation systems. Some of the reported applications of these intelligent techniques in instrumentation are given in references [x-y] which cover a wide spectrum of application in process monitoring, product inspection, and fault detection and diagnosis.

5.2 Sensor fusion

Models of processes have been built to recognize (algebraic and /or dynamic) relationships between peer process variables. The models can then be used to detect failed sensors by monitoring current readings and providing failure alarms when a measured value no longer makes sense in the context with its peer variables. Besides, a reconstructed value can often be synthesized by this model for the failed sensor while the instrument is out of service for repair.

Accurate data-based models for prediction of the process output yield have proved effective in reducing some of the expensive additives used in the process without sacrificing the process output quality or in some cases eliminating substantially a troublesome impurity in the output product. Neural nets trained on already available historical data of the plant were used in such applications. In many cases, the investment on the plant data acquisition systems is more than several times paid for by such applications of data-based process models.

Sensor validation detects failed instruments and automatically generates validated or reconciled measurements for them. It uses a two or three layer net with the inputs equal to the outputs. The structure shown on the right side of Figure I is for a two layer sensor validation net, which has no hidden units and is therefore linear.

Sensor validation uses the process measurements to predict themselves. It therefore takes advantage of the redundancy common in process instrumentation. More importantly, when a sensor validation net is trained it learns the physical relationships between the process measurements. If a calculated measurement varies from its corresponding measured value by more than a specified tolerance, then it is assumed that the instrument for that variable has failed. It follows that sensor validation uses the physics of the process to detect instrument failure, instead of using some information about the instrumentation itself.

5.2 Soft/ Virtual Sensor

The name "soft sensor" or "software sensor" has been coined to indicate an on-line neural network prediction model for a process property. A soft sensor produces a live measurement for a product property that normally would be provided by the lab. It is functionally equivalent to what has been called an "inferred property". Since a soft sensor can replace a hardware analyzer, it has also been given the name "virtual analyzer". The history of soft sensor development and early applications is given in [1] and [2]. The ease with which these single-output models can be built from existing process and lab data has led to a flood of soft sensor applications across multiple process industries. The main attractions of this technology versus hardware analyzers are lower installed cost, lower maintenance cost, higher reliability, and greater accuracy.

Harsh environments such as those prevailing in certain process units involving caustic materials may not allow certain key process variables to be measured directly. Usually laboratory tests involving long time delays are needed to determine how well production of certain product is proceeding. If such laboratory results are unsatisfactory , the production that have occurred as well as those occurring in the interim period until correction could be made will be off-specification and hence result in a loss to the company. However, if a model could be constructed to accurately predict the production results, on-line, process corrections can be effected in real-time. This means that, effectively, the values of "soft" or "virtual" sensors can be synthesized by teaming the mathematical relationships between the future laboratory results and the current values of related variables that are being measured on-line.

The powerful empirical modeling method of neural networks has simplified the procedure of making single-output property models from process data. Soft sensor applications are spreading across the process industries at a present rate of about three per day. This paper presents soft sensors and itemizes the procedure of building a soft sensor. Field examples are provided from refining, petrochemicals, polymers, pulp and paper, and mining.

5- FUTURE TRENDS

1. The standards are based around "open systems" which provided for transportability (portability) of programs and operating systems from one vendor to the next. Examples of standards are ISA's SP-88 Batch standard or the IECI 131 logic programming standard

the PLC vendors are supporting. Additionally, there are "defacto" standards like DDE (dynamic data exchange), OLE (object linking and embedding) for linking Windows programs and OPC which is OLE for Process Control that are making life for the user easier today. With the ability to use system components supplied by different vendors an environment of heterogeneous products can now communicate in a homogeneous fashion.

2. Intelligent field devices and client-server configurations are becoming the norm for any architecture (PLC, DCS or PC based).
3. The control functions move to the field devices and the central control system changes its size and function in life. Smaller, more powerful hosts with less 1/0 due to FieldBus are right around the comer. The decisions as to where control resides (field device or host) is the next challenge to engineers with FieldBus being implemented in the near future.
4. Operating systems are coming down to two choices either Unix or Windows NT which means all the software developers can focus their resources and stop trying to second guess the markets direction. Windows NT which is the solution for tomorrow. Unix remains king of the hill for "mission critical" applications while NT is focusing on PLC applications where the risk is moved away from the software (until it becomes more robust). Need for real time operating system geared to mission critical applications. Still there is a strong need for a robust real-time operating system for industrial mission critical control, based on the windows NT environment.
5. Wireless communications skipping over the ISA/SP-50 FieldBus. This coupled with battery or solar powered transmitters that are non-intrusive and simply mounted to the process with adhesive is the way to go.
6. Self-validating sensors, self-repairing sensors and self-calibrating transmitters.
7. "soft" sensors that provide inferential measurements, simulated in the control system (variables that are calculated based on the process model) .
8. International manufacturing standards are adopted for the physical attributes of form, fit and electrical classifications (like Cenelec for EC-96) then we will have true global competition.
9. Develop system validation across all components of the process systems and this will include the HVAC and Environmental controls.
10. MMI level where Virtual Reality, 3-D Graphics and Voice Activated commands with journal annotations become the norm.
11. Belt & helmet mounted displays for the maintenance personnel to wear thus allowing them to read the installation / calibration manuals right there on the spot.
12. The next major shake up in our industry will probably come from the Internet where software can be leased, purchased, borrowed and supported by a remote vendor.

Industrialized versions of personal computers (PC's) have gained an increasing market share of what has been dominated by DCS systems for the continuous applications (PID) and PLC's for discrete (logic). There is a need for an open architecture hardware standard, e.g., OMAC by Ford and GM, for PC based controller for DCS systems. Among the main desired features, hot plug and play, redandance and back up operation of cards and systems, fault tolerant memory and hardware The controller expected benefits: **economical** to achieve low life cycle cost, **maintainable to** supporting robust plant floor operation, expeditious repair, and easy maintenance; allowing the integration of off-the-shelf hardware and software components into a controller infrastructure that supports a "de facto" standard environment modular permitting "plug and play" of a limited number of components for selected controller functions and **scalable:** enabling easy and efficient reconfiguration to meet specific application needs, from low to high end.

13. As hardware became robust and fast enough to support large programs software became the driving force As standards evolved choices became wider for the user allowing them to integrate multiple vendors into a hybrid system customized for their needs and matching it to their resources.

Table 3 Technology Trends

Technologies	**Today**	**Tomorrow**	**Future**
Software	x	x	x
Artificial Intelligence		x	x
Modeling		x	x
Machines and Processes			
Machines and Processes			
Computers	x	x	
Standards		x	x
Intelligent Processes		x	x
Neural Nets		x	x
Object-Oriented	x	x	
Programming			
Enterprise	x	x	x
Robotics	x		
Intelligent Software		x	x
Parallel Processing	x	x	x
Communications		x	x

CONCLUSIONS

The growth of semiconductor, networking and information technologies has had a great impact in many sectors of the industry. The impact has been more telling in the instrumentation sector applied to measurement and control industry than in many others. The result is an exciting interplay of technologies from many engineering disciplines to develop instrumentation designs that aim to make the industrial processes safer and more economical to operate.

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