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INSTRUMENTATION IN THE DAIRY INDUSTRY

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Introduction

Industrial evolution in the second half of the twentieth century was mostly influenced by four types of inter-related factors – progress in (digital) technology, advances in science, evolution of societal requirements and demands and, particularly over the past thirty years, evolution of business concepts.

Developments in digital technology and in systems theory led to major progress in sensor and information technology and a revolution in the availability of distributed control systems and open software applications. New concepts, particularly *knowledge-based* measurement and advanced control methodologies, are slowly but steadily being brought into the practice of process operation, performing on-line and in real-time.

Societal and economical factors have driven evolution in the very same direction. The increasing concern for health, safety and sustainability issues, market quality requirements, economical pressure and the evolution of company strategy from local to global and now to metanational business concepts, the so-called *knowledge* economy concepts, all together reflected on plant investment decisions, favouring process automation for cleaner and safer operation, higher product quality and improved process efficiency and productivity.

The scenario described applies entirely or can be illustrated by the evolution in dairy process engineering and operation over the past three decades.

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Discussing plant automation from a technical point of view means to discuss instrumentation, control system configurations, data communications and theoretical control structures.

The present chapter deals with instrumentation, addressing in particular both basic and advanced concepts concerning sensors and the issue of how to integrate local hardware for automatic control usually dispersed throughout the plant.

Basics of plant automation

There are well established methodological steps on the design and implementation of a control structure: i) designing and implementing an appropriate, flexible, control configuration; ii) performing first level data acquisition and process monitoring, including record keeping and first level alarms; iii) performing data interpretation (implementing second level process monitoring); iv) designing and implementing optimisation and control solutions.

In plant-wide distributed control configurations, as illustrated in Fig. 1, the backbone of transmission is all digital. Communications protocols (some open, some proprietary) ensure data transmission for centralised data interpretation, for monitoring and for plant scale optimisation. Control at sector and unit level is usually performed locally. Local level signal transmission has for many years been only analog, firstly pneumatic signals, later electric (current or voltage) signals. However, more and more, information flows also digitally between (smart) sensors and controllers.

<Figure 1 near here>

At local level, process control system instrumentation include: 1) sensors for measurement of process variables; 2) controllers, for implementing a proper (digital) control structure (e.g. PID, predictive or adaptive controller, etc.); 3) final control elements for manipulation of process inputs; and 4) support devices such as general signal conditioners of both input and output signals, electric (V/I and I/V) transducers, electric-to-pneumatic transducers and hold elements.

The offer of instrumentation and control systems is very large today. Industrial users have nowadays available through the Internet information sites of instrumentation manufacturers with most detailed information on all types of instrumentation and control systems configurations, including data communications, related to plant automation.

A relevant management decision in the automation of older plants, and most fall in this category, is on how to step from existing local control solutions into integrated distributed control. Investment on a complete new solution is high and the tendency is to try to adopt a solution that makes use of available equipment. This is often hard to achieve and leads to a final configuration that mixes too many different control equipment suppliers, with the related cost of operation and maintenance.

Measurement instrumentation

A key limitation to the application of process control is the lack of appropriate sensors for many process variables. This is quite so in dairy processes and therefore measuring techniques for on-line use in dairy industry are subject to a considerable research and manufacturing interest. Basic concepts and main measurement techniques are reviewed in this section.

Basic characteristics of sensors

A sensor is composed of a *sensing element* and a *transmitter* as indicated schematically in Fig. 2. The sensor output, analog or digital, should be a standard signal suitable to be supplied to a controller.

< Figure 2 near here>

Most transmitters respond rapidly. When the sensor element response is also fast, then measurement dynamics can be neglected when modelling process dynamics. Such a case is indicated in Fig. 3, which shows the time response of a pH electrode to a step change in pH from 4 to 7. The characteristic first-order time constant for the sensor dynamics is in the order of milliseconds ($\tau \cong 570$ ms). There are however cases where the measurement dynamics, particularly time lag, may be significant and ignoring it can lead to control difficulties.

< Figure 3 near here>

Sensors can exhibit a linear or non-linear behaviour, this being related to and expressed by the relation between the variation of the property value and that of the transmitted signal. Sources of non-linearity lie usually on the sensing element. For a linear sensor, the gain for a given calibration is constant, being the ratio between the set span and the range of the sensor output. Nowadays, with digital data acquisition, transducer non-linearities are easily incorporated in the data interpretation software and cause no practical difficulties.

Specialized sensors/measurement systems

The most important properties of dairy processes subject to measurement that reflect both process operation and product quality are classified as *objective* or *subjective*. Examples of the former are pH, temperature, flow rates, pressure, level, etc.. Sensors for on-line measurement of such properties have been available already for a long time. Properties such as taste, flavour, colour and consistency are considered as subjective and difficult to measure.

Commercial sensors applied in the dairy industry are subject to several quality constraints such as sanitary, safety and environmental requirements. A trend in the new sensor design technologies is the increasing integration of the sensing elements into silicon chip microcircuits. These new measurement devices directly incorporate all circuitry needed to self-compensate for environmental changes and yield an output that is suitably amplified for transmission to standard electronic controllers. These sensors offer the advantage of small size, reduced prices and practically no mechanical parts to wear out.

Next, measurement techniques and instrumentation for most important objective properties in the dairy industry are considered.

pH

pH measurements are of paramount importance for quality control in milk fermentation and related processes. Just as examples: inadequate pH can be a cause of discoloration, excess free whey and excess or inadequate tartness; pH changes are related to the viscoelastic properties of yoghurt and they are also correlated to the bacteria physiological state in lactic acid fermentations. Also, the final pH value is normally a feature of the final product: fermentation converts lactose (milk sugar) to lactic acid, causing a pH drop into the range of 4.25-4.5; rapid cooling at the correct lactic acid level then stops bacterial action.

pH electrodes can be in direct contact with food, as far as they meet sanitary requirements. In general terms pH measurements, particularly in conjunction with electrical conductivity measurements (see below) constitute an important means for continuous, real-time, process monitoring.

Temperature

In industrial applications the main measuring devices for low temperatures (below 250 ºC) are based either on thermoelectric effects (thermocouples) or on resistance changes (platinum RTD - Resistance Temperature Devices, thermistors, etc.). Measurement characteristics, particularly sensitivity and the degree of (non-)linearity favour the use of platinum RTD, the most widely employed being the so-called PT100 device.

Thermal processing is a key stage in the majority of dairy process operations. As example, during the pasteurisation phase of yoghurt production temperature is raised up to 85-90 ºC to destroy undesirable micro-organisms and restructure the protein to improve viscosity. Then a cooling is performed to 40-45 ºC such that the sterile mix is ready for inoculation. Also, freezing and refrigeration are used to maintain the products in such a condition that growth of unwanted micro-organisms is prevented. In general, these type of operations and process units require a reliable and accurate temperature monitoring and control system.

Level, density or interface level

Liquid height, density or interface level between two liquids can be measured either by differential pressure (d/p cells) sensors or by measurement of buoyancy force on a displacer suspended in a liquid. An electronic transmitter converts the output of the sensing element into an appropriate output analog or digital signal.

Nowadays instrumentation companies offer for the dairy industry a variety of special transmitters for level monitoring and control applications in inventory tanks and CIP (clean-in-place) vessels.

Pressure

In most process operations, particularly when thermal processing is required, pressure regulating is one of the essential control loops. Pressure sensors are thus amongst the most commonly used on-line sensors. Differential-pressure (d/p) cell transmitters either for gauge or absolute pressure are the solution generally adopted.

Thermal conductivity

Thermal conductivity expresses the ability of a substance for conducting heat. The most common thermal conductivity probes consist of an assemble of an electrical heated wire and a temperature measurement system (based on thermocouples or thermistors) from where heat fluxes are measured and heat conduction is inferred.

Thermal conductivity measurements find wide application in dairy chemistry and biochemistry and in food engineering. The measurement of thermal conductivity by *Line heat source probes* may be used to determine in-line the coagulation time of milk for curd and yoghurt production and may be helpful to automate these processes, aiming at maximising cheese and yoghurt yield. Coagulation time may be detected by the sharp increase in the temperature difference between probe temperature and initial milk temperature.

Electrical conductivity

Electrical conductivity (G) expresses the ability of a substance or media to conduct electricity. It is employed for quality control and further finds on-line use in identifying feature points of fermentation states. For example, electrical conductivity measurements allow distinguishing between the urease activity and the acidification activity in lactic acid fermentations.

In a dairy plant where many fermentations are performed, either simultaneously or sequentially, the real-time prediction of fermentation completion time is very important for scheduling raw material supply and energy utilisation. Data-driven models (e.g. neural networks based) relating characteristic properties of the fermentation state (model outputs) to pH and electrical conductivity (model inputs) can be firstly identified (trained) and subsequently employed for monitoring of the fermentation process and for prediction of fermentation final times.

Viscosity

The main equipment for viscosity measurement are process viscometers. Measurement of shear viscosity for Newtonian fluids can be performed by a capillary flow viscometer. Cone and plate viscometers are suitable for determining the shear viscosity of time-independent non-Newtonian fluids. From the process viscosity behaviour the stages of aggregation and gel formation can be described and calculated. The viscosity can finally be used as an objective measure for the control of coagulation processes.

In industrial operations involving slurries, pulps, grease or other similar media, consistency, rather than viscosity, is measured by rotation and oscillation rheometers. These devices allow for example the continuous on-line monitoring of the transition of milk fluid into a viscoelastic gel structure.

NIR spectroscopy

Infrared and Near Infra Red (NIR) spectroscopy can be used for measuring water contents, fat and proteins in liquid milk and related products *on-line* (and *Ex-situ*). This is a commonly used technique for quality control, but may as well be employed for on-line closed-loop control.

Optical Density

Optical Density (OD) is commonly employed to measure biomass concentration on-line and *Ex-situ*. The measurement principle is based on the individual or combined use of measurements of transmission, reflexion or scatter of light. The interpretation of the signal is complex, but it is normally linearly correlated to biomass concentration in diluted solutions.

Final control elements

Most control actions consist of adjusting flow rates of process input or output streams (solid, liquid or gas) or of cooling and heating fluids. Final Control Elements (FCE) are devices employed to manipulate input control variables driven by The most important FCE are flow regulator valves.

Designing a valve involves taking decisions on valve sizing, choice of body material, choice of type of valve (*signal-to close* or *signal-to-open*) and choice of flow vs. aperture characteristics (essentially linear or equal percentage valves).

Valve sizing (the computing of the valve Cv) and the choice of valve flow characteristics require consideration of hydrodynamic aspects, particularly pressure drops along the piping. The choice of material depends on the corrosive properties of the process fluid. For dairy industry stainless steel valves are most common. The decision on working with *normally open* or *normally closed* valves derives directly from answering the safety question of how should the valve stay in emergence due to energy failure.

Regulator valves are typically driven by a pneumatic signal (range 3-15 psig or 0.2-1 bar). Signals are normally transmitted to the FCE as analog current signals (4-20 mA), being locally converted by a current-to-pneumatic transducer. Alternatively a stepper motor, driven by a digital signal from the controller, can actuate valves.

On-off valves typically utilize electrical or pneumatic actuators. They are mainly used for sequential control and during start-up and shutdown procedures. Other final control elements, namely displacement devices and pumps, are more and more actuated digitally by stepper motors.

Finally, between the controller and the final control element a number of signal conditioning devices or transducers may have to be employed. For example, for distance signal transmission current rather than voltage signals have to be used. If the control signal is a voltage signal, the minimum sequence of transducers to be employed consists of a voltage-to-current converter near the controller output and a current-to-pneumatic converter near the FCE. As another example, when manipulating power (e.g. pumps) a low current buffer amplifier will always have to be employed connected to the actuator.

5. Digital control equipment

Digital control instrumentation represent the new standard and indeed they have brought in a major change of mindset with respect to control system structures and solutions. They brought in new procedures concerning communications and calibration routines. They offer the computing power required for implementation at local level and in real-time of advanced model-based monitoring and control algorithms (software sensors, predictive control etc.). They enable through the available distributed control architectures the implementation of plant-wide monitoring, optimisation and control solutions.

Distributed control systems

A distributed control system (Fig. 3) is simply an arrangement whereby control devices and computer processing power are distributed through a network instead of being centralized.

Main devices in a distributed control system are essentially microprocessor-based sub-systems such as *programmable logic controllers* (PLC), *smart sensors*, *supervisory and engineering stations* and other I/O devices (*FieldPoints, device integrators, etc.*). All devices in the network must be integrated with proper hardware and software for communications.

PLC are today’s industrial standard for local digital control. They are reliable special purpose computers for control in the industrial environment, consisting of a set of Input-Output (I/O) modules and a programmable CPU. They can perform Analog-to-Digital (AD) and Digital-to-

Analog (DA) Conversion and have special purpose digital I/O ports (PLCs were originally designed mainly for event control). PLC have normally proprietary programming languages.

Smart sensors are devices that through their digital system can be connected in the network, communicating bi-directionally with the other devices. Particularly, they accept remote commands for remote calibration.

General purpose computers (PC, Workstations) may be interconnected in the control system network to carry out inferential measurement procedures, high-level data analysis, supervisory duties or more sophisticated dedicated control tasks.

FieldPoints (FPs) are modular I/O devices that connect a bank of analog and/or digital I/O modules to an industrial network, being able to perform AD/DA signal conversion.

The key feature of a distributed control system is thus that the measurement and control tasks are distributed out into the field, enabling cost savings (e.g. in wiring), higher flexibility and above all, higher level of information and knowledge, this expectedly resulting in improved management performance. Integrated hierarchical control configurations may be built where high-level tasks like process supervision and optimisation are fully integrated with the low-level data-acquisition and local control tasks.

Communications standards

Industrial communications refer to the networking hardware and software, together with the respective communication protocol.

A number of industrial network standards, designed to meet different application requirements, are available today, viz. - Ethernet, DeviceNet, Fondation Fieldbus, PROFIBUS and CAN (Controller Area Network). Details for these industrial network standards can be found in Table 1.

Some of them specify low-level sensor-controller-actuator communication protocols (like CAN and DeviceNet) whereas others are specially oriented for distributed control systems in the process industries (Fieldbus and PROFIBUS). They differ on communications bus specifications on velocity of data transfer, on communications protocol employed and on the communications model. For distributed control systems in large factories Fieldbus and PROFIBUS are the two most important standards. Fieldbus is fully compatible with existing (older) analog 4-20 mA communications.

A special remark should be made on Ethernet. It is the most widely used local area network (LAN) technology. The original and most popular version of Ethernet supports a data transmission rate of 10 Mb/s. Newer versions of Ethernet called "Fast Ethernet" and "Gigabit Ethernet" support data rates of 100 Mb/s and 1 Gb/s (1000 Mb/s). An Ethernet LAN may use coaxial cable, special grades of twisted pair wiring, or fiber optic cable. "Bus" and "Star" wiring configurations are supported. Ethernet devices compete for access to the network using a protocol called Carrier Sense Multiple Access with Collision Detection (CSMA/CD). Ethernet conforms to the IEEE 802.3 specifications and runs commonly under the TCP-IP - protocol (Transfer Communication Protocol – Internet Protocol; although many others are possible). The Fieldbus standard has adopted a second alternative for the physical layer that is based on Ethernet, thus providing a solution for factory-to-factory communication.

Basics of analog-to-digital and digital-to-analog signal conversion

Any digital control system contains a data acquisition interface that performs AD/DA conversion. Such tasks are commonly performed by standard computers with AD and DA cards, by FieldPoint modules or by PLC.

It is worth examining basic aspects of the data acquisition and control problem: i) chain of information from the 'process property' to the ' binary word in the computer'; ii) how such information is made available in the computer; ii) the control decision; and iv) the control action, i.e. the chain between the 'binary decision variable' and the Final Control Element.

Data acquisition

The data acquisition chain is represented schematically in Fig. 2. The design stage of the data acquisition system should start with a qualitative analysis, addressing the following main considerations:

- The sensor should be chosen with the objective of maximising sensitivity for the desired measurement interval. This means that calibration should be such that the sensor measurement span should match the measurement interval and be mapped into the full range of the output signal.
- Industrial ADC are nowadays standard. A 12 bit analog to digital converter is generally sufficient. The input range is not a problem, assuming that the required signal conditioners are available.
- Signal conditioning should be such that the sensor output signal V_0 is transduced into a signal V_2 that exhibits the same range as that of the ADC. This situation maximises the overall resolution of the acquisition chain.

Still in the design stage, the quantitative analysis must be performed in steps from the process to the computer, viz. –

- The sensor delivers normally an analog electrical signal (V_0), which should be a known invertable function of the process property P. Assuming for simplicity a linear relationship, eqn. (1) holds:

$$V_0 = k_0 P + z_0 \tag{1}$$

- This signal will generally undergo some form of conditioning (transducing, amplification, attenuation, etc.), depending mainly on aspects related to compatibility and range of transmission signals (V_1 and V_2). These type of transformations can usually be adequately expressed by linear relationships of the form:

$$V_1 = k_1 V_0 + z_1 \tag{2}$$

$$V_2 = k_2 V_1 + z_2 \tag{3}$$

- Considering a N bit ADC, with an input range [$V_{\min}$, $V_{\max}$], the digital word D, corresponding to V_2 is given by:

$$D = \mathrm{INT}\left[\frac{V_2 - V_{\min}}{V_{\max} - V_{\min}} 2^N\right] \tag{4}$$

The corresponding discretization error is given by $\pm 0.5\frac{V_{\max}-V_{\min}}{2^N}$. For a 12 bit converter this error is well inside industrial requirements, generally lower than all other errors in the chain.

- Of another kind, but relevant, a decision must be taken on the sampling time (T) to be adopted in the implementation. A simple rule of thumb, often employed in industrial applications is that the sampling time should be of about one-tenth of the process characteristic time.

The implementation stage of local signal acquisition corresponds to effectively programming the multiplexing, analog-to-digital conversion (ADC), data reading (binary value *D*) and data decoding (getting the property *P* from the binary value *D*).

- For each scanning (multiplexing and data reading through commands such as *peek*, *get, in…*) of input channels, performed at every time interval T, programming of data decoding is performed by successively computing the values from the binary word D to the property P, through eqns. (5) to (8), respectively the inverse of eqns. (5) is the inverse of eqn. (4) to (1):

$$V_2 = V_{\min} + (D + 0.5)\frac{V_{\max} - V_{\min}}{2^N} \qquad (5)$$

$$V_1 = (V_2 - z_2)/k_2 \qquad (6)$$

$$V_0 = (V_1 - z_1)/k_1 \qquad (7)$$

$$P = (V_0 - z_0)/k_0 \qquad (8)$$

- At this stage, process values are available in the data acquisition application for all types of desired actions, namely: data interpretation, data plotting, book-keeping, analysis of alarms and related actions, computing of control actions and output of control commands.

Control action

It is out of the scope of this paper to analyse control algorithms. Assuming that a control decision has been taken, given by a binary word *C*, such command is transmitted from the control system to the final control element through an elementary chain including the DAC (with a hold element), and probably (in the more general case where the final control element is a valve) a signal conditioner, a buffer amplifier and a current-to-pneumatic signal transducer (Fig. 2). The following comments should be added:

- The industrial standard for DA converters is normally of 12 bit. Most common ranges of output signals are 0-10 V or 4-20 mA. Assuming that the DAC is set for a voltage output, eqn. (9) represents the DA conversion, where N is the number of conversion bits of the DAC , V_{ref} is the reference voltage (corresponding to an output interval of 0-V_{max}, with $V_{max} \cong V_{ref}$) :

$$V_3 = V_{ref} * C / 2^N \qquad (9)$$

This specific DA conversion equation should be known for design, but it is not explicitly employed in the programming. The programme only includes the output command (*out, poke*, *flush*, *put*, etc., depending on the programming language) of the binary control action C .

- Signal conditioning is not a main problem. It is clear that care must be taken to ensure that wiring is correct, that care has been taken in ensuring that *instruments and source grounds are of good equivalent level* (a comment that also applies to wiring in AD lines) and that appropriate buffer amplifiers to protect control devices from high currents are employed. Most output signals are converted in standard current signals and directly fed in the Final Control Element, which incorporates the relevant current-to-pneumatic converter.

6. Advanced topics

Two topics closely related to the state of the art in both information technology and systems theory are now brought to discussion, viz.- *how to make measurable what is not so*, a dream of Galileo (1564-1642) about 400 hundred years ago; and *how to integrate information and manage large scale systems*.

Software sensors

In many cases key process variables and characteristic parameters, namely kinetic and transport parameters, are not available directly on-line and in real-time, either because they are really not measurable or simply because measurements may be expensive and/or unreliable.

Software sensors are algorithms for the on-line computation of those state variables and parameters that are not measurable in real time, from more easily accessible (accurate and inexpensive) related measurements. The concept is closely related to those of *inferential measuring* and of *state observers* largely discussed in the specialised systems engineering literature. The design and implementation of software sensors provides in some cases a suitable answer to cope with the lack of instrumental sensors. It may require the computational power of a dedicated computer in the distributed control network, a requirement that nowadays represents no technical or economical problem.

A software sensor relies on a process (subsystem) model that establishes the relationship between measured and estimated properties. Hence, the key for success (or failure) of a software sensor is on the availability of knowledge/information about the relationship between measured and unmeasured properties, i.e. the accuracy and robustness of the underlying model. With respect and in the context of dairy industries, the kinetics in fermentation tanks are the most difficult part of the process to model. Traditionally, designing adaptive observation/estimation algorithms, of which the most reported technique is the Extended Kalman filter, circumvents the problem. This type of methods require a number of simplifying assumption that are not always acceptable. More recently, *knowledge-based* software sensors have been reported. They rely on AI (Artificial Intelligence) models like analytical neural networks (ANN) and fuzzy or hybrid neuro-fuzzy models, combined with mechanistic expressions of process behaviour. Results reported in the literature are excellent in ability for prediction with minimum information requirementsfor implementation is very substatantial, this hindering its industrial application in a wide scale, on the short term.

Measurement of subjective properties

At present operators use their human senses, i.e. smell/aroma, feel, taste as a gauge for the acceptability of products. Hence, the main challenges to the modern measuring techniques are to provide information not only regarding traditional (bio)chemical and physical variables (i.e. objective properties), but also and mainly to monitor final consumer quality parameters considered as subjective.

Properties such as *taste*, *flavour*, *colour*, and *consistency* are subjective properties that are extremely important for process operation in the food industries. At present the operator uses his human senses, i.e. *smell/aroma, feel, taste,* as a gauge for the acceptability of products. Measurement techniques for subjective properties are reported to be under intensive investigations. The *electronic nose* concept is maybe the most well known example. The *electronic nose* mimics the human nose to detect specific aromas and smell. This technology is today commercially available. *Image analysis* is today a well-developed technique. Properties such as material *visual aspect* can be inferred from these techniques, serving this new information for further and new automatic processing to be carried out.

Factory-to-factory automation

As a final point, with the advent of Internet it becomes clear that the information flow scheme of Fig. 1 in an automated factory may move down in the hierarchy. As this technology becomes reliable and secure we may speak of a factory-to-factory (worldwide) automated information flow and distributed processing. Whilst this does not represent a state-of-routine automation solution, it represents a real management tool in the context of the prevailing business concepts.

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Abbreviations

ADC – Analog to Digital Conversion
ANN – Artificial Neural Networks
CIP – Clean-In-Place
DAC – Digital to analog conversion
FCE – Final Control Element
LAN – Local Area Network
NIR – Near Infra-Red
PLC – Programmable Logic Controller

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Appendix – Short glossary

Final Control Element (FCE) - a device, driven by controller signals, employed to directly manipulate process variables. Usually the controller output (digital) signal cannot be applied directly to the process. It is first converted by a transducer to a standard (analog) current signal, which activates the FCE. The most widely employed FCE are flow regulator valves. *In situ* – In the original location.

In vitro - Pertaining to a biological reaction taking place in an artificial apparatus.

In Vivo – Pertaining to a biological reaction taking place in a living cell or organism

On-line – Pertaining to equipment capable of interacting with a digital computing system.

Protocol – Set of rules and formats that govern the way in which devices communicate with each other.

Range – Interval defined by the upper and lower limit of values of an input variable over which a device can be calibrated.

Real-time – Pertaining to a data-processing system that controls an ongoing process and delivers its output or controls its inputs not later than the time these are needed for effective control.

Sensing element (primary detector) – A generic name for a device that detects either the absolute value of a physical quantity or a change in value of the quantity and converts the measurement into a useful input signal for an indicating or recording instrument.

Sensitivity – The input signal variation required to produce the minimum detectable output signal of a device.

Sensing element – a generic name for a device that detects either the absolute value of a physical quantity or a change in value of the quantity and converts the measurement into a useful input signal for an indicating or recording instrument.

Sensor – a generic name for a device composed of a sensing element and a transmitter, also termed measuring device. It is implemented for acquiring information on the current status of the process output variables.

Signal transducers (signal converter) – A *transducer* that converts one standardized transmission signal to another.

Span – the difference between the highest input value and the minimum input value set for a measurement device within its work range.

Transducer – Any device or component that converts an input signal of one form to an output signal of another form (note: this is a general term and definition and as used here applies to devices such as sensing elements, transmitters and signal transducers).

Transmitter – (1) a transducer that responds to a measured variable by means of a sensing element and converts it to a standardized transmission signal, which is a function only of the measurement; (2) a device that converts a variable into a form suitable for transmission to another location.

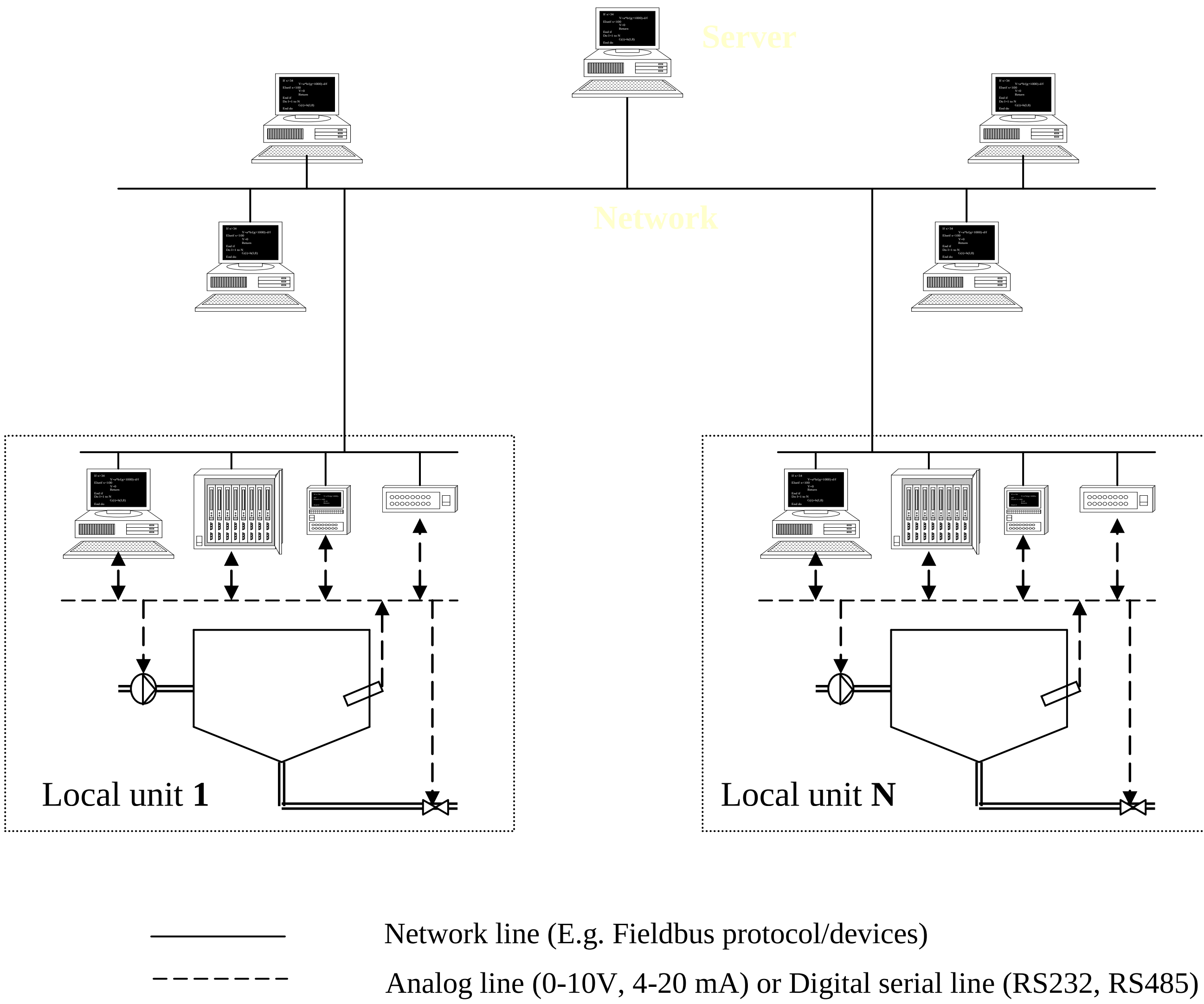

Figure 1: State-of-the-art instrumentation for process control: devices, signal transmission and information flow

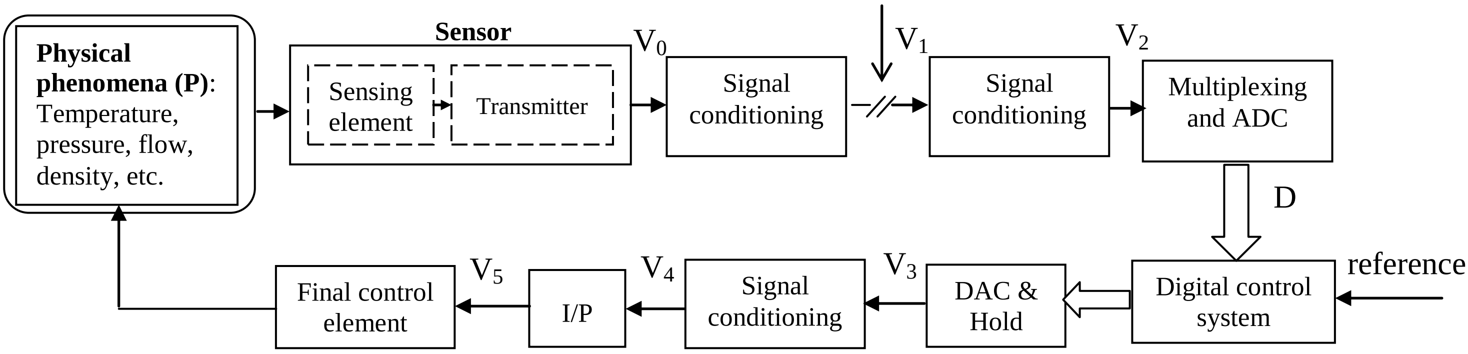

Figure 2. Schematic representation of stages in a digital control system

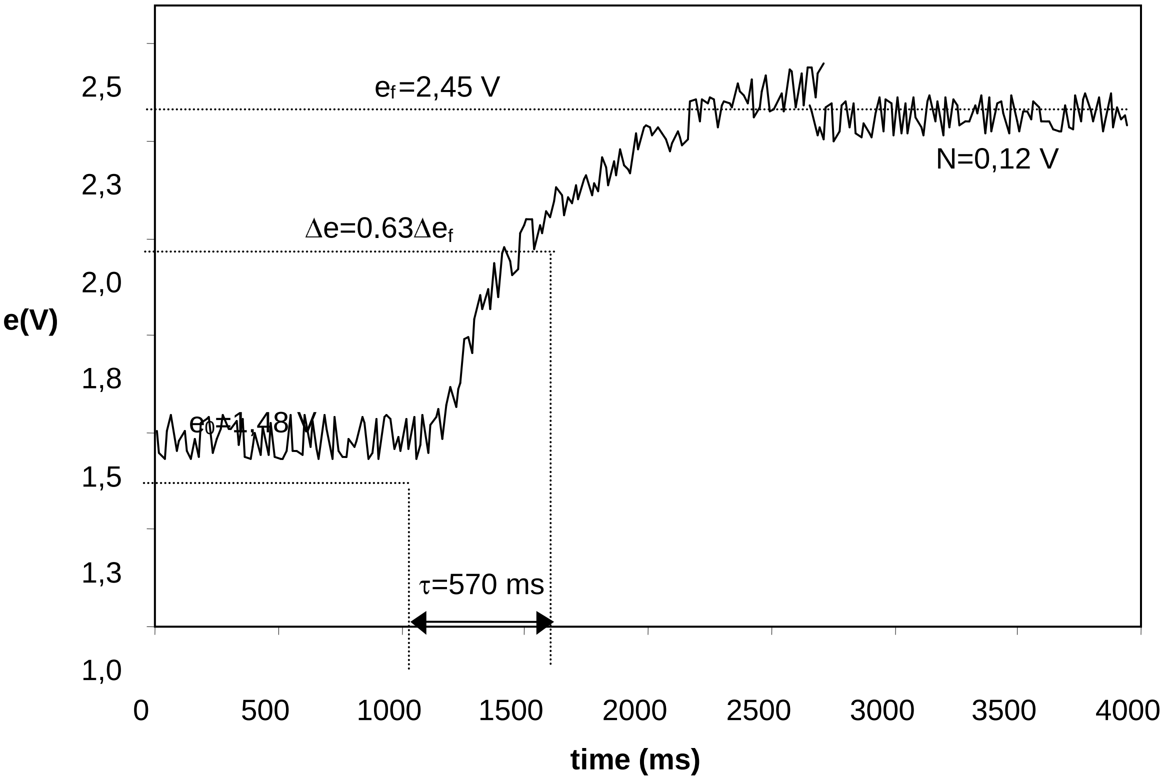

Figure 3. Time response of a pH electrode to a step change in pH (4-7)

Table 1 – Industrial Communications Standards

Standard	**Description**	**General features**	**Application areas**
DeviceNet	Low-level network designed to connect industrial devices (sensors, actuators) to higher level devices (controllers)	Powered bus consisting into 2 separate twisted-pair cables Built on CAN protocol Producer-consumer model for data transfer	Mainly manufacturing industries
Foundation Fieldbus	Digital network standard designed specially for distributed process control; Expected to substitute the 4-20 mA analog standard	H1 powered 31.25 Kb/s bus (Standards ISA S50.02-1992; IEC 61158-2) or High-Speed 10/100 Mb/s Ethernet (HSE) Fieldbus (communication) protocol (IEC 1158-2)	Mainly process industries
PROFIBUSDP/FMS/PA	Family of communication standards. Leading open Fieldbus system in Europe; PA is mainly used in the process industries	DP and FMS : RS485 serial line with baud rates up to 12 Mb/s PA: Fieldbus standard (IEC 1158-2)	Manufacturing and Process automation
Ethernet	EtherNet is an Industrial standard that defines only the physical layer; Some industrial standards are built on top of Ethernet	• Coax cable with BNC connectors or telephone wiring with RJ45 connectors or fiber-optic cable (10-1000 Mb/s) (Standard IEEE 802.3) • Ethernet does not define itself the communication protocol. It runs commonly under the TCP-IP protocol	Mainly in LANs for PC-to-PC comm.. .
CAN Controller-Area-Network	Designed originally for in-vehicle automotive communications.	CANbus (Serial bus) with CANbus communication protocol.	Also for process industries