INTELLIGENT SENSOR TECHNOLOGY

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Introduction

The remarkable advances in microelectronics and data processing technology have made possible the miniaturization of sensors, integration, and the combination of data from a number of sensors. As a result, even in the field of measurement, some of the intellectual activity which could previously only be carried out by human beings is being mechanized. This has started to occur in large production facilities.

Single sensors are used to detect individual state variables such as temperature. However, what the operator wants to know is whether the plant is operating properly or not. This means a system in which, when there is some indication of unstable operating conditions of the plant which might give rise to a dangerous situation such as runaway, an alarm is given without delay and the operating condition is displayed. In fact, not even a single meter is provided on the operator's control console; all the required data is displayed on a CRT. Instead of the signals from the individual sensors being presented to the operator, these are processed to obtain information as to whether the plant operating condition is normal or abnormal, and this is what is presented to the operator. In other words, the data from a number of sensors is processed and combined to obtain a signal as if from a single 'operating condition sensor'. Such a system is called an intelligent sensor system.

The term 'intelligence' first appeared in the engineering field when artificial intelligence (AI) was proposed by Minsky and others at MIT. Such 'intelligence' clearly meant human intelligence or mental activity. Now, however, the meaning of the term has been broadened and we speak of, for example, an 'intelligent building', meaning a building which is pre-fitted with a local area network for convenience in data communications.

The Japanese Industrial Standards (JIS) defines a sensor as 'the first element in a system that converts a measured quantity related to the condition in question into a signal'. But what is meant by an intelligent sensor? Terms such as 'smart sensors' and 'sensor fusion' are being used, but have as yet no firm definition. The term 'intelligent' of course implies a relation with human intelligence, but intelligent sensors are not just an extension of the definition of sensors given above. This book has therefore been compiled for the reference of engineers and students interested in intelligent sensors. It describes the current state of the art of intelligent sensors based on a number of practical examples.

Ryoji Ohba
March 1990

Contents

1 Intelligent Sensors

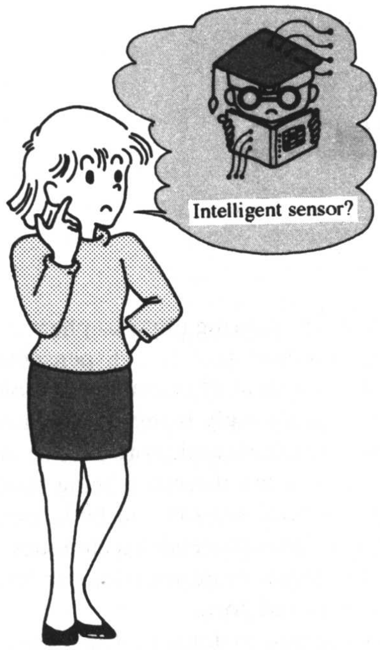
Measuring devices are devices for observing and measuring physical phenomena, and are an extension of human perception and intellect that is indispensable for the scientific investigation of nature. With the development of scientific technology, new and more difficult to detect phenomena are increasingly being investigated. These have produced a requirement for faster, more sensitive and more precise measuring devices. In the field of sensor technology, sensors are therefore being miniaturized and implemented in solid-state form so that several sensors can be integrated and their functions combined. Also, by using digital signal processing techniques, in which remarkable development has been achieved, the necessary information can be extracted from the detected data and presented in a required form.

This process has led to the appearance of sensor systems that can replace some human intellectual activity, i.e. some human intelligence. In this chapter, we shall outline the background of intelligent sensor technology and the concept of intelligent sensors. Lastly we shall explain the organization of this book.

1.1 MAKING SENSORS INTELLIGENT

Control systems are becoming increasingly complicated and generate increasingly complex control information. Control must nevertheless be exercised, even under such circumstances. Even considering just the detection of abnormal conditions or the problems of giving a suitable warning, devices are required that can substitute for or assist human sensation, by detecting and recognizing multi-dimensional information, and conversion of non-visual information into visual form. In systems possessing a high degree of functionality, efficiency must be maximized by division of the information processing function into central processing and processing dispersed to local sites. With increased progress in automation, it has become widely recognized that the bottleneck in such systems lies with the sensors. This is the background to the demand for making sensors intelligent.

Such demands are difficult to deal with by simply improving the sensor devices themselves. Structural reinforcement, such as using arrays of sensors, or combinations of different types of sensors, and reinforcement from the data processing aspect, by a signal processing unit such as a computer, are indispensable. In particular, the data processing and sensing aspects of the various stages involved in multi-dimensional measurement, image construction, characteristic extraction, and pattern recognition, which were conventionally performed exclusively by human beings, have been



tremendously enhanced by advances in micro-electronics. As a result, in many cases sensor systems have been implemented that substitute for some or all of the intellectual actions of human beings [1], i.e. intelligent sensor systems.

Sensors which are made intelligent in this way are called 'intelligent sensors' or 'smart sensors'. There seems to be no settled definition of these terms [2]; however, Middelhoek and Hoogerwerf [3] adopt the definition 'at least one sensing element and signal processing circuitry integrated on the same chip'. The definition adopted by Breckenridge and Husson [4] of NASA is:

> The sensor itself has a data processing function and automatic calibration/automatic compensation function, in which the sensor itself detects and eliminates abnormal values or exceptional values. It incorporates an algorithm, which is capable of being altered, and has a certain degree of memory function. Further desirable characteristics are that the sensor is coupled to other sensors, adapts to changes in environmental conditions, and has a discrimination function.

Scientific measuring instruments that are employed for observation and measurement of the physical world are indispensable extensions of our senses and perceptions in the scientific examination of nature. In recognizing nature, we mobilize all the resources of information obtained from the five senses of sight, hearing, touch, taste and smell, etc., and combine these sensory data in such a way as to avoid contradiction. Thus, more reliable, higher-order data is obtained by combining data of different types. That is, there is a data processing mechanism that combines and processes a number of sensory data. The concept of combining sensors to implement such a data-processing mechanism is called 'sensor fusion' [5]. This also comes within the purview of intelligent sensors.

1.2 INTELLIGENT SYSTEMS AND SENSORS

The present tendency is for systems to become increasingly complex. Traditionally, the engineers concerned with such systems have been required to have a high level of education. This trend cannot be expected to continue indefinitely. Specifically, it would be practically impossible to expect the educational level of the engineers, i.e. the operators involved with such systems, to be for example of doctorate standard. It is therefore necessary to devise a human/machine system that can be maintained and whose operation can be completely understood by technicians of suitable general background and intelligence. In such an 'intelligent' system, human mental activity is partially substituted for by machinery. New sensors and new methods of processing the data collected by such sensors are therefore needed.

Let us take an example of more than ten years ago, when microprocessors first appeared. At this time, heavy engineering provided the basis of the economy. In particular the iron and steel industries represented a large proportion of Japanese trade earnings. Automation and computer control of the steel-making process had already been practically completed and automation of the stages of working and obtaining the final product was being put in hand. In the final step of the process of rolling H-section steel from a slab, there is a step in which the H-section steel is cut to a prescribed length. Previously, the measurement of length and cutting were performed manually after waiting for the H-section steel to cool down following the hot rolling. That is, after the final step of hot rolling, measurement and cutting to the desired length was required. However, it was necessary to rationalize the cooling yard, waiting time, and manpower, etc., that were necessary for this. A specific problem was to measure the length of the H-section steel whilst still in motion at the outlet of the rolling mill immediately after hot rolling.

This problem was solved [6] by constructing a measuring system, which was in fact an intelligent sensor system, as follows. Let us assume that a person is standing next to the red-hot H-section steel as it runs out of the mill, and is observing it minutely. What will such a person do to find the length of the H-section steel that is galloping past in front of his eyes? The engineers reasoned as follows. If we know the instant at which the head of the H-section steel passes in front of our eyes, and the speed of movement of the H-section steel thereafter at every instant, the present length from the head to the point of observation can be found by integrating the speed. The instant at which the head passes can be measured. But is it possible to measure continuously the speed of a red-hot object? The engineers considered various ways of achieving this, but finally had to give up hope of continuous measurement of the speed. However, as the next-best alternative, they decided on deducing the motion of the H-section steel from the instants when the head of the steel passed several observation points. The measurement system which they devised in order to achieve this is shown in Figure 1.1.

In more detail, optical beam-type switches were provided at several predetermined observation points. The time indicated by a clock linked to these switches when the light beams were interrupted by the head of the H-section steel was read. This was then input to a computer. We can consider this information as being represented within the computer by a graph of the motion of the head of the H-section steel as shown

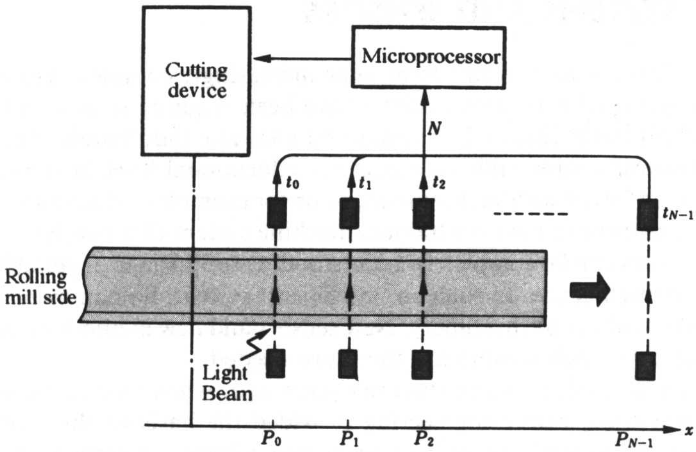


Figure 1.1
Intelligent measuring and cutting system

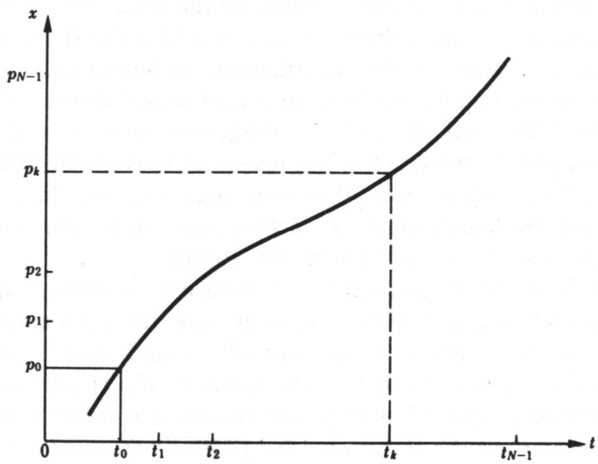


Figure 1.2
Movement of head of H-section steel beam

in Figure 1.2. Using this hypothetical graph, we can now deduce the time at which the head of the H-section steel passes a given reference point. (The distance from the origin to this reference point is the required length of the H-section steel.) Thus the time at which a cutting device that is positioned at the origin of the coordinates should be actuated in order to obtain H-section steel of the desired length can be found. Incidentally, in the system shown in Figure 1.2, this length can also be measured by deducing the position of the head of the H-section steel at that time point from the graph showing the motion of the head of the H-section steel described above, and reading off the time at which the tail of the H-section steel passes after cutting off a light beam positioned at P_0.

The example described above was only a very basic form of intelligent sensor system, since it merely involved automation of measurement that had previously been performed manually. One would now probably not bother to call it an intelligent sensor system, but this sensor system does however incorporate the essential features of an intelligent sensor system, which are as follows.

(1) Data of a single quantity to be measured is output by co-ordinated processing of output data obtained from a plurality of sensors: i.e. sensor fusion and data processing.

(2) Data processing by computer: the importance of software.

(3) As a result, implementation of a system substituting for the human mental activity of measurement of length: performance of an intelligent operation by machinery.

(4) Use of a sensor system to implement recognition of a measurand which could scarcely be determined from the output of a single sensor: that is, the system implements the mental activity of human beings of combining information.

If such a system were to be implemented nowadays, the optical beam switches and the clock linked to these would probably still be the same. However, the computer that determines the starting time of the cutting device from the times at which the head of the H-section steel passes the various points would probably be replaced by a microprocessor on a single chip. This could then be accommodated in the control unit of the cutting device, so that the cutting device itself would be made intelligent.

1.3 ARRANGEMENT OF THIS BOOK

This book introduces the present situation regarding intelligent sensor technology with the aid of some practical examples. It explains how intelligent sensor systems are assembled, how the sensors are organized and combined, and how they function. It is intended as a reference for engineers aiming to develop such intelligent systems in various fields, or for students intent on becoming engineers in this field. Chapters 1 to 3 introduce the concepts of intelligent sensor technology and the basic features of the associated sensor technology. Next, Chapter 4 discusses the use of sensors for environmental and equipment diagnosis, with special reference to sound and vibration sensors; Chapter 5 discusses sensors used in intelligent machines, i.e. robots; Chapter 6 describes making automobiles intelligent; and Chapter 7 describes making structures such as buildings, etc., intelligent. In each field, the intelligent sensor technology is described with reference to practical examples. Finally, Chapter 8 examines future prospects. A list of the various elementary sensors used in sensor technology is given as an appendix at the end of the book.

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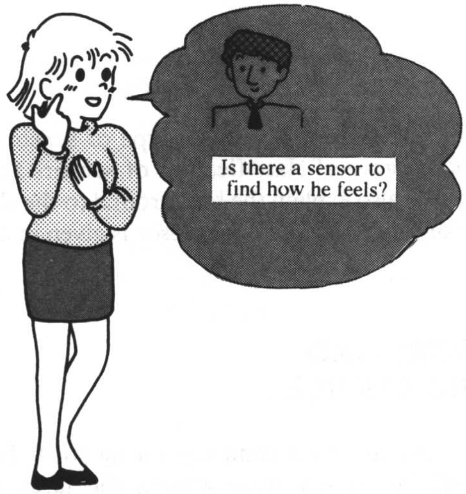
2 Types and Applications of Sensors

In the design of a sensor system, selection of a suitable type of sensor is vital. In this chapter we explain a method of general classification of sensors for reference in the design of intelligent sensors. We also explain the background to the classification and application of sensors. A list of types of individual sensor is given in an appendix at the end of the book.

2.1 CLASSIFICATION OF SENSORS AND HOW TO MAKE A SUITABLE CHOICE

Consider the classification of sensors as like a company hiring staff. How should personnel to be selected as staff be chosen from among the large number of

possibilities? Usually a profile of the type of person required is prepared and used as a basis for advertising for applicants, from whom the most suitable are selected. This profile is condensed from specific examples of the company's evaluation standard. For example, qualifications and/or skills relevant to the work after hiring, specialization, state of health, age and personality considered from the point of view of the composition of the staff of the work-place, or sex and nationality, or in some cases family composition and school and even friendships would be relevant.



Similarly when sensors are employed a suitable choice must be made depending on the object, application, precision, system, environment of use, and cost, etc. In such cases consideration must be given as to what is an appropriate evaluation standard. This question involves a multi-dimensional criterion and is usually very difficult. The evaluation standard directly reflects the sense of value itself applied in the design and manufacture of the target system. This must therefore be firmly settled at the system design stage. In other words, the questions: 'What quantity is to be measured, for what purpose?' and 'Is this quantity really necessary or is there another more appropriate quantity?' must be carefully examined. In the following discussion, we shall assume that such careful consideration has already been given to the purpose and subject of the measurement.

In sensor selection, the first matter that must be considered by the system designer is determination of the subject of measurement. The second matter to be decided on is the required precision and dynamic range. The third is ease of use, cost, delivery time, etc., ease of maintenance in actual use, and compatibility with other sensors in the system. The type of sensor should be matched to such requirements at the design stage. Sensors are usually classified by the subject of measurement and the principle of the sensing action, etc. Here, however, we shall take a look at a classification of sensors from the point of view of sensor selection for intelligent sensor systems.

2.2 SENSORS CLASSIFIED BY TYPE OF INPUT AND BY THE SUBJECT OF MEASUREMENT

We shall now classify sensors by the type of input, in other words, by the paradigm of the subject of measurement. Sensors of various measurement paradigms may be considered, from the simple (existing classical sensors that have the object of sensing a single physical quantity such as dynamic quantities like force, pressure, or displacement) to the complex (sensing of sensation variables such as whether a person is in an elated or depressed mood, or whether the 'feel' of a surface is pleasant or unpleasant).

This is the most usual method of classification. The sensor is classified in accordance with the physical phenomenon that is needed to be detected and the subject of measurement (see Table 2.1). Examples are voltage, current, displacement, and pressure. Classifications in general textbooks mostly adopt this system. The list of sensors given in the appendix also follows this method.

Many sensors were developed with specific objectives. There are therefore very many different types of sensors, which it would be impossible to cover in the limited space available. There are many books about sensor technology. Explanations of the basic principles of sensors are given in, for example: *Sensa nyumon* (*Introduction*

Table 2.1
Sensed items classified in accordance with subject of measurement.

Category	Type
Dynamic quantity	Flow rate Pressure, force/torque, torsion Displacement, length, volume, position Level Rotation Speed, acceleration Sound and vibration spectra Distortion Direction (direction of force of gravity) Weight ON–OFF, proximity, passage
Optical quantities Electromagnetic quantities	Light (infra-red, visible, or radiation), vision, image; voltage, current, frequency of vibration, phase, magnetism
Quantity of energy or quantity of heat	Temperature Heat Humidity, dew-point
Chemical quantities	Analytic sensors, gas, odour, concentration, pH, ions
Sensory quantities or biological quantities	Touch, vision, smell