Introduction

Instrumentation: Where Knowledge and Reality Meet

Instrumentation comprises scientific activities and technologies that are related to measurement. It is a link between physical, chemical and biological phenomena and their perception by humans. Constantly evolving, instrumentation changes how we live and plays a major role in industrial and life sciences; it is also indispensable to the fundamental sciences. In order to be credible, all new theories must undergo a series of experimental validations, of which instrumentation is the cornerstone.

Is curiosity a distinguishing human trait? Certainly, this characteristic leads us to question, to understand, to explain, and finally to "know". The more we explore, the broader our range of investigation becomes. Since the 18^{th} century, scientific and technical knowledge have undergone an exponential expansion, an explosive growth of combined learning, but this kind of growth leaves us with unanswered questions. In this context, instrumentation serves to stimulate scientific knowledge in the junction between theory and experimental practice.

Even before humanity developed a body of scientific knowledge, signs of technological progress had appeared in ancient civilizations. By 5,000 BC, humans had fashioned stone tools, and later began working in metal around 3,800 BC. Ancient Greeks, such as the philosopher Aristotle, who lived in the 4^{th} century BC, were probably among the first thinkers to put forward logical explanations for observable natural phenomena. Democritus, a contemporary of Aristotle, already thought of matter as being formed of miniscule, indivisible particles. However, the

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instrument of measurement most important to the Greeks was the gnomon, or needle of a sundial. The gnomon helped the Greek mathematician Euclid, living in the 3rd century BC, to measure the earth's radius by simultaneously observing the shadow cast by the instrument on two points of the same parallel. After this discovery, developments in mathematics, numerical theory and geometry followed, with Euclid's ideas dominating the world of science up until the Renaissance. From the 16th century onwards, Galileo, Newton, and Descartes brought forward new approaches that were truly objective, which meant that all new scientific theories had to be verified by observation and experiment. It was in this era that scientific instruments began to be widely developed and used.

The example we will discuss here will show, without forgetting Euclid's contribution as cited above, how instrumentation helped to join knowledge and reality. In the 18th century, both maritime navigation security and the possibility of complete world exploration were limited by current imprecision in measuring the coordinates of a ship traveling anywhere on Earth. The problem of calculating latitude already had been resolved some time before, thanks to fairly simple geometric measurements and calculations. Determining longitude presented more problems. As soon as a relation was established between the idea of time and space, scientists, especially astronomers, proposed using the movement of the stars as a cosmic clock: one example was the rotation of Saturn's satellites, discovered by the French astronomer Jean-Dominique Cassini in 1669. However, developing this idea further proved difficult and complicated. Determining longitude by relying on a measurement of time difference in relation to a given location required a precise measurement of time that was impossible to attain with the tools then available. To give an idea of the order of magnitude, let us recall that at the Equator, a nautical mile is defined as the length of a terrestrial curve intercepting an angle of a minute. The time zone being equivalent to 15 degrees, the lapse of time of a minute equals 15 minutes of curve or 15 nautical miles. Thus a nautical mile is equal to 4 seconds.

The problem was resolved in 1759 by the English clockmaker John Harrison, who invented a remarkable time-measuring instrument, a sea clock or chronometer that was only 5 seconds off after 6 weeks at sea, the equivalent of just 1.25 nautical miles. This revolutionary clock marked an important step in the search for precision begun in 1581 with Galileo's discovery of the properties of regularity in a swaying pendulum, a principle taken up and developed further in 1657 by the Dutch physician Christiaan Huygens, inventor of the pendulum clock. John Harrison's invention produced a number of other technological innovations such as ball bearings, which reduced friction that caused imprecision and errors. His chronometer stimulated progress in a number of other fields, among them cartography, leading to clearer, more geographically accurate maps. Today the Global Positioning System (GPS) stills depends on time measurement, but with a margin of error of less than several centimeters, thanks to atomic clocks with a margin of error that never exceeds that of a second every 3 million years!

These kinds of remarkable discoveries became more frequent over time in all scientific and technological fields, often resulting in new units of measurement named after their inventors. Instead of the inexact and often anthropomorphic systems then in use, it became necessary to create a coherent system of measurement that could be verified by specific instruments and methods from which reproducible and universal results could be obtained. An example of one older unit of measurement was the "rope of 13 knots" used by European cathedral builders to specify angles of 30, 60 and 90 degrees. Other measurements long in use such as the foot and the inch obviously could not meet the criterion of reproducibility but did allow for the emergence of standards and the development of somewhat more regular measurements. The usage of these often varied from region to region, becoming more widespread over time. The ell, for example, differed not only according to place but also according to usage. The first tentative step toward a coherent system was clearly the British Imperial System, adopted in 1824 by Great Britain and its colonies. The SI, an abbreviation for the International System of Measurements today in use throughout much of the world, dates from 1960 and allows scientists to join all measurements in use to a group of specific and carefully chosen basic measurements, thus giving birth to a new field of science that could not exist without modern measurement: metrology.

As the development of the metrology shows, access to information, facts and measurements, all crucial to the interaction between knowledge and reality, also serve to stimulate technological innovation. Making use of the latest technology in the fields of sensors, measurement, communications, signal processing and information, modern instrumentation plays an unprecedented role in progress and science. An interdisciplinary field, instrumentation is itself present in almost all scientific disciplines, including the fundamental sciences, engineering science, medicine, economic and social sciences, promoting exchange of ideas and data between different scientific communities and researchers. The particle accelerator ring developed by CERN, the European Organization for Nuclear Research, is perhaps the newest instrument of measurement. With numerous subsets of specific measurements, this impressive instrument allows scientists to explore infinitely small things by studying and discovering new types of particles. As well, astrophysicists have attempted to validate certain elements of the big bang theory by more and more refined observations of the universe, making use of a vast array of extremely sophisticated technologies, among them the Hubble space telescope.

Resolving instrumentation issues frequently involves a very broad spectrum of theoretical abilities, as well as mastery of experimental techniques. This means that research teams in business and university laboratories, on the individual level, must have scientists who can invest time in multi-disciplinary research; the teams themselves must also serve as conduits between research teams belonging to complimentary disciplines. This form of interdisciplinary activity, in which research teams are able to imagine and work out applications of their work beyond their own fields, is an extremely attractive challenge. But will this necessarily lead to innovative concepts – and if so, according to which scientific principles?

The reality is that of the vast range of solutions widely available to resolve any problem of measurement, very few are actually suitable. The emergence of an innovative and optimum system often appears as the result of an ingenious combination of a group of methods and technologies drawing on diverse disciplines. This approach does not necessarily mean a major development has occurred in each of the involved fields; it does, however, require in-depth knowledge of these fields. The innovation resulting from this mastery is not less rich, open and dynamic in terms of scientific, technological and economic terms, resulting as it does from interdisciplinary exchange.

The objective of this work on measurement and instrumentation is to present and analyze all the issues inherent in conceiving and developing measurement, from the source of a signal (sensor) to conveying quantitative or qualitative information to a user or a system. Le Colloque Interdisciplinaire en Instrumentation or Interdisciplinary Conference on Instrumentation held in November 1998 in Cachan, France gives a general survey of the range of this field (see C2I'98). This book cannot claim to be exhaustive. However, throughout the chapters, we give examples of our main theme – the idea of a system that brings together technologies, methods and complex components relating to theoretical, experimental, and scientific skills. All of these draw on the essence of instrumentation.

To give a well-known example of this theme, we look at the car, an object that has paradoxically retained the same function over decades even as it has never stopped changing and evolving. We are all aware of how new technologies, especially in the fields of micro-electronics and industrial computer science, have changed cars. We notice the continual appearance of new scientific concepts whose names and acronyms (such as the Antilock Braking System (ABS), the Enhanced Traction System (ETS) and controller area network (CAN) operating system) become familiar through widespread publicity and advertising of vehicles. In fact, the car as a symbol has become more interesting and inspiring than functions such as airbags or digital motor control which often make use of new, though hidden, technologies. These technologies usually develop within widely varying constraints such as safety, reliability, ease with which problems can be diagnosed and repairs can be made, and cost. Such technologies also are affected by marketing factors like style and comfort. The car is thus an illustration of an impressive technological expansion that has taken place within the parameters of science and within the parameters of socio-economics.

This book has been written for technicians, industrial engineers, undergraduate students in the fields of electronics, electrical engineering, automation, and more generally those in disciplines related to engineering science who require in-depth knowledge of how systems of measurement are developed and applied. The chapters follow a fairly linear progression. However, our text falls into two complementary but somewhat different halves.

The first half of the book discusses fundamental ideas and issues of measurement and presents a range of physical phenomena that allow us to obtain measurable sizes and develop methods of pretreatment of signals. In these early chapters, our discussion of instrumentation focuses mainly on components. The second half of the book concentrates instead on the aspect of systems by looking at how data are processed and used. These two different emphases are linked in Chapter 6, which presents the carrying out of integrated functions, showing how microtechnologies have shown great promise in the fields of sensors and instrumentation.

Using the example of the car, the first chapter defines the links between instrumentation, measurement and metrology, explaining how units and tools of measurement are developed. Chapter 2 presents the general principles of sensors, while Chapter 3 gives a detailed description of the general principles of optical, thermal and mechanical sensors, and how these may be used in developing measuring tools and sensors. Chapters 4 to 6 discuss a range of methods and technologies that allow for a complete measuring process, from the conception of an electronic conditioning of signals, passage through discrete time, data conversion and quantification, filtering and numerical pretreatment.

Chapter 7 progresses from the idea of components to that of systems, concentrating on somewhat more technical aspects by discussing instrumentation in terms of microsystems, accelerometers, and pressure sensors. Chapters 8 to 11 present information on how systems and measurement networks are created, how models of interaction between sensors and their environment are developed, as well as ideas concerning representational space, diagnostic methods and merging of data. Chapter 12 summarizes the previous chapters and discusses the idea of intelligent systems and sensors, to which signal processing imparts valuable qualities of rapidity, reliability and self-diagnosis, available to us thanks only to the miniaturization of complex mechanisms that integrate a number of complex functions. We have chosen several examples from a specific field: the production of cars.