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MEASUREMENT SCIENCE – AN EXAMINATION OF ITS CURRENT STATE AND LINES OF ADVANCE

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Abstract – The paper outlines the content and organisation of the generic concepts and principles of measurement and instrumentation. It argues that recent changes of technology and the political, economic and social environments demand a review of those principles and considers the resultant challenges and lines of advance. It distinguishes between measurement and instrument science. It considers the challenges presented by applications of measurement outside the physical sciences. It highlights the effect of advances in computing and the resultant convergence the principles of measurement and instrumentation and the sciences underlying systems and information. It considers special problems of sensing and actuation. It points to the design orientation of measurement and instrumentation principles and applications of the systems approach to measurement and instrumentation. It examines indirect measurement. Problems of errors and uncertainty are pointed out. Finally it points to the approaches of knowledge management.

Keywords: Measurement Science, Instrument Science.

1. INTRODUCTION

There exists a science of measurement and of the instrumentation by which it is implemented. This science is developing rapidly as a result of the push of advancing technology and the pull of changing requirements. The nature, scope and organisation of that science are of great practical importance for the nature and organisation of education in measurement, for learned society activities and for the storage and transfer of knowledge. They require, therefore, regular review and debate.

The paper argues that recent technical advances, as well as political, economic, and social changes, have been so significant that they demand examination of the nature and organisation of measurement science. It outlines such an examination and reviews some tasks and lines of advance of the discipline**.**

2. DEVELOPMENT OF MEASUREMENT SCIENCE

There are generic, systematically organised, concepts and principles of measurement and of the instrumentation by which it is implemented.

Measurement is as old as material civilisation. It had its origins in counting. It developed in Antiquity through applications in trade, calendar determination and surveying. It was the basis of the voyages of discovery and of the growth of modern science. By the end of the nineteenth century there developed in the physical sciences well established scales and standards of measurement and an extensive and diverse arsenal of measurement techniques and apparatus [1-6]. As knowledge advanced, it was organised as a catalogue of techniques for measurement in the laboratory and like applications. The writings of Kohlrausch [7] were a model.

The development of electronics and the possibilities and requirements of applications outside the laboratory, such as automatic control, drove rapidly forward the progress of measurement. The progress greatly increased the capabilities of physical measurement and the diversity of apparatus and applications. To enable this greatly increased corpus of knowledge to be effectively stored and applied, it began to be organised into a systematic body of concepts and principles.

Starting with pioneering work of Draper at MIT [8] and some parallel work of Kuhlenkamp [9], endeavours were made to systematize the principles of instrumentation. The establishment of IMEKO, the International Measurement Confederation gave an impetus to this work [10].

The nature and scope of Measurement Science has been regularly reviewed and a broad consensus achieved. An analytical review of that consensus of measurement and instrumentation generic concepts published in 1994 reports that consensus [11]. It has an extensive bibliography giving credit to the developers of the discipline. The essential features of those generic concepts and principles can be summarised as follows. Measurement is viewed as an information process, representing aspects of the external world by symbols.

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Instruments and instrument systems are viewed as information machines. Measurement apparatus is described, analysed and designed as systems. A central characteristic of this approach is the use of mathematical models to describe and analyse measurement systems and their components. The systematic approach to instrumentation is oriented towards principles of design of equipment.

Current technical, social and economic changes support the general organisation of the subject, but present new challenges and lines of advance**.**

3. TECHNICAL, ECONOMIC AND POLITICAL ENVIRONMENT

3.1 Technical Environment

The principal technical change affecting measurement is the advance of computing. As the result of the rapid growth of capability and lowering of costs of information technology, once information about a measurand has been acquired from the object under measurement and carried by an electrical signal, the functions of processing, displaying and effectuating that signal are in general performed by standard computer technology. This leads to a significant convergence of the concepts and principles of measurement instrumentation and those of information technology. Further advances in computer hardware and software have transformed methods of analysis and design of measuring systems. Finally the Internet has transformed the methods of representation, manipulation, storage and distribution of knowledge.

3.2 Economic, Social and Political Environment

The last two decades have seen major economic and political changes in the world and the turbulence continues. This has altered the environment in which measurement technology operates and this in turn poses challenges to the underlying science.

Globalisation demands internationally implemented standards and internationally recognized systems of quality assurance. This makes measurement technology a key enabler of industry and trade in all countries. It presents challenging problems of quality measurement.

There has developed a rigorously commercial approach to technology. The time from initiating the development of a product and its introduction to the market is short. The life cycle of a product is short. It makes measuring equipment design knowledge-intensive.

The complexity and rate of change of modern technology, economics and society have led to the ever widening applications of measurement based information in management, governance and the general understanding of all aspects of our life. This makes demands on measurement theory and philosophy.

4. SCIENCE OF MEASUREMENT AND SCIENCE OF INSTRUMENTS

It has become conventional to use the term Measurement Science to describe the generic, systematically organised, concepts and principles of measurement and of the instrumentation by which it is implemented.

It is, however, useful to distinguish between the domain of the concepts and principles of measurement and that of the concepts and principles of instruments.

Measurement is defined, in the wide sense, as the assignment, by an objective, empirical process, of symbols to attributes of objects and events of the real world, in such a way as to describe them. Measurement Science is the body of systematically organized concepts and principles underlying measurement. Measurement is the basic tool of natural science and technology, which is its origin and paradigmatic application. It now extends to all domains of human enquiry and discourse, such as Psychology, Economics and Sociology.

Instruments are machines, or systems, that acquire, process and effectuate information from the natural world. There is a systematically organised body of concepts and principles underlying the design and analysis of instruments, which may be termed Instrument Science.

The science of measurement and the science of instruments overlap, but are not identical.

Measurement in the natural sciences is predominantly performed by measuring instruments. In the natural sciences the bodies of knowledge concerning measurement and instrumentation. Outside the natural sciences, say in Economics and Sociology, measurement does not in general employ instruments in the sense used above.

Measurement in the natural sciences is the major area of application of instruments. However instruments are widely used for purposes other than measurement, for example in many applications of imaging and detection. In any case measuring instruments are only a special class of the more general class of information machines.

5. PROBLEMS AND LINES OF ADVANCE IN FOUNDATIONS OF MEASUREMENT

5.1 Logical and philosophical foundations

The logical and philosophical foundations of measurement are well established. They are is based on the representational theory. The theory is based on the viewing of the real world as empirical relational systems and measurement as a process of mapping them into symbolic relational systems. The theory has been extensively presented in the literature [12-18]. An outline has been presented in [18]. The theory has been extensively considered and important contributions have been made by Mari and Rossi [19-22].

The above theory is valid for all applications of measurement. However, there are aspects of foundational principles of measurement that require development.

5.2 Measurement in the physical sciences

Measurement in the physical sciences is the paradigm of all measurement. Its foundations are generally recognised as valid. There is of course a well established system of units and scales of measurement [23] and a widely agreed vocabulary [24]. Nevertheless there are some problems in the foundations of measurement in these sciences, which require attention.

Firstly, while the representational theory of measurement is applicable to physical measurement and originated in it, it is not generally used in that field. Details of the application require development.

Secondly, there are physical properties, such as hardness, the measurement scales for which do not form part of the general system of units and scales [25]. They require attention.

Finally the problem of quantum measurement requires further study [26].

5.3 Widely defined measurement

Measurement is now being applied in all domains of human enquiry and discourse. The applications extend to the social and psychological sciences. They are employed in management.

The wide range of applications demand changes of approach to the foundations of measurement, from that employed in the physical sciences. The changes are outlined in [27, 28]. In many domains outside the physical sciences the development of appropriate measurement processes and scales presents a research agenda. The problems of measurability are a key issue in many applications. The range of applications and the challenges of measurement in those domains are presented in [29].

There is a need to develop a general, integrated framework of concepts and principles of the foundations of measurement in all domains. This must be linked to the foundations of all forms of symbolic representation, that is general Semiotics [30].

6. MEASURING INSTRUMENTATION AS INFORMATION SYSTEMS

Measurement Science is mainly concerned with the concepts and principles of the description, analysis and design of measuring systems.

In a modern measurement system a sensor acquires information from the observed system and converts it into an electrical signal. That signal is then conditioned, that is converted into a signal that can be processed by standard information technology equipment. Following processing the signal is then output to a display, an actuator, or passed to further processing. The system is controlled by operators, if it is not wholly automatic, through standard human computer interfaces. The core functions of measuring instrument systems are thus implemented in standard computer and communication hardware and software.

Measuring systems are thus substantially analysed and designed as information systems. This leads to the general overlap of the principles of measurement instrumentation, information systems, control and communication. It can be argued that these sciences are in fact a single discipline and should be treated in an integrated way.

Applications to measurement problems of the methods of information theory, the theory of signal processing and of information and knowledge processing, do not, in general, present special theoretical problems.

Modern instrumentation systems handle, in an integrated way many inputs concurrently. Imaging and image processing constitutes an integral part of the modern principles of instrumentation [31]

However there are aspects of measurement systems that are distinct from the concepts and methods of the information sciences and require special treatment. They are considered below.

7. SENSING AND ACTUATION

Sensing and actuation are components of instrumentation systems that are not implemented by standard information technology equipment. Sensors and actuators are information machines. Their knowledge, information and signal processing functions can be described, analysed and designed using standard information processing principles.

However, their implementation require design and analysis in terms of the physical effects on which they are based, their geometry and material properties.

There is a great diversity of sensors and actuators regarding input and output variables and the physical effects on which they are based. Information about them is therefore still organised as catalogues.

Systematically organised concepts and principles for sensors and actuators are based on two linked approaches. Firstly on their description and analysis using mathematical models. Secondly on a methodology of their design.

The modelling of instrument elements has been reviewed in [32]. Progress has been reviewed in [33].

The principal aspect of progress has been the advance in the power of detailed models of sensors and actuators relating their function to their geometry and material properties.

There is a need for wider application of computer aided fluid dynamic modelling of sensors.

Similarly, the extensive software that is available for modelling, analysis and design of optical systems needs to be integrated into the wider methodology of sensor modelling.

Progress is being made in the development and application of functional mathematical modelling systems such as bond graphs and Modelica. The thermodynamic relations for reversible systems have been effectively applied to sensing and transduction. [34]. They have been applied for a long time to electroacoustic transducers. There is considerable interest in the application of the relations in chemical and biochemical systems. However, there is more to be done to integrate them into the framework of the analysis of sensors and actuators**.**

The organisation of information about sensors and actuators, based on mathematical models has been reviewed in [34]. However the organisation of knowledge is incomplete.

There is more work to be done to extend existing schemes to the representation of distributed parameter systems, fields and waves. Further, the application to chemical sensors awaits development.

The general principles of the systems approach [35, 36] are the basis of the analysis and design of measurement instrumentation.

Measurement systems are never conceived, or used, in isolation. They are always a component of a larger system, or supersystem.

The object under measurement is always part of that supersystem. Specific problems in measurement arise in the interaction between sensing and the measured object. Methods of the modelling of this interaction, which are always based on physical effects, are an integral part of concepts and principles of measurement instrumentation.[30, 31]

The data that are the product of measurement are always further processed. This processing is always part of the supersystem. In this respect measurement systems must be treated by the methodology of information systems design [37, 38]**.**

Alternatively, measurement systems form part of a control system. The design of a control system involves always the consideration of the measurement system. In particular in multivariable systems, it involves the location of sensors.[39, 40]

The application of the systems approach to measurement instrumentation is a major factor in the convergence of the concepts and principles of measurement and those of information technology.

9. DESIGN ORIENTATION

The multiplicity of measurement systems with respect to measurands, principles of operation, forms of embodiment and the like means that the most economic organisation of the knowledge about them should be based on the concepts and principles of their design.

The methodology of measurement systems design is outlined in [41].

The basis of the methodology of measurement systems design is the systems approach, discussed above.

The essential aspect of modern instrumentation, as again discussed above, is, that once information about the measurand has been acquired by the measurement system and the measurement signal conditioned, subsequent processing is realised by standard information technology hardware and software. The design methodology for the information processing subsystems is provided by Computer Science.

The design of sensor and actuator subsystems is however realised in terms of physical embodiment. This is best approached by the systematic methods of engineering design. [42].

The design of sensors and actuators involves two types of problem. The first is the generation of a design concept. The second is, given the concept, to determine the detailed form and dimensions of the device.

The latter involves no fundamental problem. With the advance of computing methods, it is possible, for many sensor and actuator types, given an appropriately formulated model of a design concept, to determine, by computer analysis and optimisation, the form and dimensions of the device to be realised. The advance of computer modelling methods and their integration into design environments is an important task.

The generation of design concepts is increasingly better understood, with advances in design studies and progress in the investigation of artificial intelligence [43]. Enough is understood to assist instrument designers in the task of design concept generation, but not enough to automate the task, or to make it algorithmic rather than heuristic. The most advanced methods rely on searching of catalogues of design concepts. The development of such catalogues, based on mathematical models, and of suitable search methods is an attractive line of research.

9. INDIRECT MEASUREMENT

There is a core problem of measurement that has not been properly integrated into Measurement Science. That science has been mainly concerned with measurands that can directly act on sensors and are then further processed, that is with measurands that characterise the flow of energy or matter.

However, an important class of measurement problems is the measurement of properties, or internal variables, of a system that are not thus accessible. Measurement is performed by exciting the observed system by a measured stimulus, measuring the response, and evaluating the measurands from the stimulus-response pair, in general using a mathematical model of the system. This class of problems is properly a part of Measurement Science.

The problems have, in general been treated in connection with the design of control systems. They are also related to problems of signal processing.[44]

The proper integration of the study of system identification and parameter estimation into Measurement Science is a significant challenge.

Important problems from the point of view of Measurement Science is the employment of models the structure and parameter of which correspond to physical variables of significance. Further non-linear systems present difficulties [45]. The problems are illustrated in [46].

10. UNCERTAINTY AND ERRORS

The problems of uncertainty in measurement and of errors arising in measurement systems are most characteristic area of Measurement Science.

A major and influential advance has been the publication of GUM [47]. This has defined the problem and presents a systematic treatment of the topic on a sound scientific basis. However, GUM does not exhaust the field. There remain challenges and problems to be addressed

Among these is firstly the consideration of dynamic measurements and uncertainty. Secondly there is the analysis of error source in instrumentation using mathematical models. There is the related problem of error avoidance and compensation. Sources of error in digital instruments await further study.

11. KNOWLEDGE MANAGEMENT PERSPECTIVE

Traditionally knowledge has been organised into disciplines in accordance with the requirements of teaching it in higher education. To an increasing extent the new perspective of knowledge management needs to be considered for application in the area of measurement and instrumentation. A discussion of this approach is given in [48].

The influence of the Internet on Measurement Science is argued in [49].

12. CONCLUSIONS

Measurement Science is a body of concepts and principles that has changed in content and organisation as a result of changes in technology and the political, social and economic environment. It is an active discipline with a significant research agenda

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