TECHNOLOGICAL AND METHODOLOGICAL

ADVANCES IN MEASUREMENT

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AKADÉMIAI KIADÓ, BUDAPEST

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ACTA IMEKO 1982

Proceedings of the 9th IMEKO CONGRESS of the International Measurement Confederation held from the 24th to the 28th May 1982 Berlin-West

VOL. I.

SENSORS AND TRANSDUCERS

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PREFACE

The Proceedings of the 9th World Congress of the International Measurement Confederation are presented once again under the title of the Congress proper, carried out between the 24th and 28th May, 1982 at the International Congress Centre of Berlin-West. The subtitle "ACTA IMEKO 1982" serves to identify the work as a member of the series of Congress records published triennially ever since 1958.

The title of this newest member of the ACTA IMEKO family marks once more the determination of the organizers to alloy the practical accomplishments of instrument technology with the theoretical achievements of measurement science. This aim was first pronounced in the formulation of the Call for Papers issued to the general public early in 1981 and the response — subjected to the cautious scrutiny of the International Papers Selection Board — yielded a range of valuable papers, well reflecting the prime intentions of the initiators of the IMEKO IX programme structure.

In accordance with instructions formulated by the General Council — supreme body of IMEKO — at its 1981 Session, the level of selection has been raised notably, even if this meant a reduction of the number of papers ultimately presented and discussed at the World Congress. By this policy the National Organizing Committee could assure more time to round-table discussions arranged outside the Technical Sessions, thus enabling congressists to participate in both functions.

The volumes of ACTA IMEKO 1982 contain the full text of all papers presented at the Technical Sessions of the Congress after the necessary editing, to assure a degree of uniformity and technical level required from a scientific work of this nature. A satisfactory linguistic level also had to be assured by the editors as far as possible. Only very few papers bear an asterisk, indicating that the text was reproduced in the original, unedited version, since a complete rewriting would have endangered the authenticity of the original contents.

The earliest possible publication obliged the editors and publishers to utilize with minor changes the original manuscripts submitted by the authors for reviewing. Despite an emphatic request for the use of standard-faced typing, such uniformity could not be assured in all cases and the editors present their apologies for the resulting non-uniform typographical appearance of these volumes.

As to the structure of the Proceedings, a considerable departure had to be undertaken against that of the Congress. This must be attributed to the decided differences between the requirements of the two media concerned. The editors hope that these structural changes considerably enhance the readability of the present volumes and assure a better conformity with the complex structural demands of our field of science, as expected from a compilation of this nature.

As at all previous IMEKO Congresses, the host Member Organization — in this case the VDI/VDE Gesellschaft Mess- und Regelungstechnik in the Federal Republic of Germany—provided by far the largest number of papers, while the others were distributed amongst authors from 22 other countries and Berlin-West. This — and the total presence of participants from 32 countries — document a growing international interest in the work of IMEKO. Let us hope that a world-wide distribution of these volumes through the technical libraries of both the developed and the developing countries will further advance the common cause of measurement and instrumentation in all continents.

Thanks are due in this endeavour to the organisers of the scientific programme of the 9th IMEKO Congress, to the contributors of the papers proper and to Akadémiai Kiadó, the Publishing House of the Hungarian Academy of Sciences, for once again assuring an early and attractive presentation of these volumes.

Prof. György Striker
Secretary General of IMEKO

FOREWORD

While smaller symposia impart special knowledge within limited fields, the aim of the large triennial IMEKO Congress should be to give a general survey on measurement science. Especially, it should promote the exchange of ideas between different fields and give a clear view of new general trends.

In comparing these proceedings with those of previous Congresses, there are indeed some striking differences and distinct new trends visible. Recent developments in technology, particularly in large scale integrated circuits and in microprocessors, are having a profound effect on measuring systems and all of their elements and subsystems. New methods may now be implemented that were previously not feasible for technical or economic reasons. For example, numerous chapters are devoted to automatic visual inspection, to image processing, to automatic diagnosis systems, and to velocity and flow meters using correlation methods, all of which are based on powerful signal processing hardware. At the same time, such new technologies often require novel methods, algorithms and measurement strategies. It is this fruitful and challenging interrelation between new hardware developments and new theoretical concepts which is meant by the Congress Theme "Technological and Methodological Advances in Measurement".

The technical programme was developed by the National Programme Committee, based on the reviews of the International Papers Selection Board, and finally decided on by the General Council of IMEKO. I would like to express my gratitude to the members of these committees for their excellent cooperation and for the large amount of work they did. I also acknowledge the great care taken by the authors in preparing their manuscripts which are presented in these volumes and which we hope will aid the development of measurement science.

Prof. Dr. Ing. Franz Mesch
Chairman of the National
Programme Committee

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PLENARY LECTURES

SMART SENSORS

by

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The proliferation of the microcomputer in measurement and control applications has brought about an unprecedented demand for new measuring instruments adapted to service in the environments and at the performance, quantity and cost levels appropriate to these applications. In the specific case of automobile engine control, the result has been the first mass-produced, high performance sensors for a variety of physical parameters.

System designers were quick to see the advantages which could be realized if the microcomputer were "tailored" to the sensor by specific software, but these advantages can only be realized at the sacrifice of part interchangeability if the two devices are separated physically. However, sensor developers are beginning to develop new instrument concepts which from the outset embody a real-time dedicated microcomputer integral to the sensor package - the "smart sensor". Some of the obvious advantages are:

- A relatively noise-immune digital output signal
- Linearization of the sensor by the microcomputer
- Automatic standardization where physically feasible
- Correction for cross-parameter effects, such as temperature, by means of integral lower performance sensors for these parameters and computation in the microcomputer.

The net effect of this approach is to change the goal of the sensor developer from insensitivity to all extraneous paramters to characterizability for these parameters. The smart sensor can also be readily calibrated automatically if its design incorporates an electronically programmable read-only memory.

The smart sensor concept permits as well the realization of totally new approaches to measurement, which require significant real-time computation to operate. For example, flowmeters utilizing real-time cross-correlation of a flow "signature" have been developed.

The past decade has also seen great advances in the mass-production of large numbers of miniature sensors by batch techniques, most notably by silicon/ photolithographic methods adapted from microelectronics processes. Unlike the conventional smart sensor approach, where the goal of the designer is primarily to reduce systematic sensor uncertainties by means of computation, the soft sensor concept utilizes the microcomputer to reduce random uncertainties by means of statistical measures. For example, an array of ten pH sensors has been realized on a small silicon chip. Together with the microcomputer, this permits the computation of the mean pH value and the standard deviation.

Keywords: Sensor, smart sensor, microcomputer, microprocessor, transducer.

1. INTRODUCTION

The latter part of the 1970's saw the proliferation of microcomputer controlled gasoline engines in passenger cars in the United States and indeed worldwide. The driving forces which caused this revolution in automobile design were the concurrent requirements for reduced emissions, improved fuel economy and an acceptable level of driveability and comfort. This change occurred very rapidly. In the mid-1970's only a few of the automobiles produced in the world had electronic engine control; these controls were implemented in analog electronics. In 1980 and 1981 the majority of the passenger cars produced in the United States had at least one type of microcomputer-based electronic control. Worldwide about 50 percent of all the cars produced in the western world included some form of electronic engine control.

To complete an electronic engine control, in addition to the microcomputer and its interfacing electronics, sensors for the key control parameters were required, as well as actuators to effect the control of the engine. The key problem area has been the development of moderate to high performance sensors which could live in the very difficult automotive environment, operate with bounded accuracy for long periods of time and be mass producible at low cost. For example, in 1980 some 5 million high performance manifold absolute pressure sensors were produced for passenger car engine control, whereas it is doubtful that one million pressure sensors of this quality had ever been produced in the whole world prior to 1975.

Indeed this accomplishment marks a significant event in the history of sensor development. It is the first time that instruments with this level of performance have been mass-produced as interchangeable, low-cost parts. Perhaps the most significant aspect of this event is that it proves that whenever a demand for large scale production of a low cost, high performance sensor exists solutions can be found to satisfy the need. Because the microcomputer is being applied to control functions in a wide variety of applications, some of which involve widely used products, this lesson cannot be ignored, for such applications will require sensors to complete the control design.

The progress of the passenger car electronic engine control has been quite well documented (1-3), as has the development of suitable on-board sensors (4-7). All of the sensor concepts which are emerging as dominant today are based upon well-known measurement principles. Only a few original sensor design concepts have even reached the prototype stage (8-10), though many entirely new methods of sensor manufacture have been developed. This rather depressing statistic can possibly be attributed to the long period of lethargy in sensor development from 1960 to 1975; during this period many sensor technologists moved into other fields and few new engineers entered the instrument professional community. One may speculate that the saga of passenger car sensors is far from over, and that it represents a fertile field for imaginative sensor design.

While we may justly call the 1970's the decade of the mass-produced sensor, it is interesting to look ahead into the 1980's to see if we can discern the next likely break-through-type event which will occur in the sensor art. I would like to propose that the most probable significant development in sensors during the 1980's will be the inclusion of a dedicated microcomputer in the sensor design as an integral component. Such sensor designs are beginning to be called "smart sensors". The widespread adoption of the smart sensor* concept in developing new sensors will, I believe, revolutionize the field of sensor development at least as radically as the mass production of automotive sensors did in the 1970's. To utilize a microcomputer to read out the electrical signal from a sensor is not novel. To merit the name of smart sensor the device must employ the microcomputer in more than just a "hang on" mode. By the term smart sensor we mean a device which incorporates a real-time integral component microcomputer dedicated to the measurement intended. The microcomputer is essential to achieving the required performance and indeed may be essential to obtaining a meaningful measurement at all. The characteristic that the microcomputer operates in real time ordinarily precludes the concept of timesharing the microcomputer with other purposes. The microcomputer and the transducer portion of the sensor are so interrelated that the replacement of one part or the other would imply the necessity for recalibration.

2. SMART SENSORS

The reasons for designing a sensor with integral intelligence are various. For those smart sensors which have been designed up to now, the microcomputer has often been used to alleviate output interface problems by providing a serial digital noise-immune link to the system with which the sensor communicates. Another important use of the smartness of the sensor has been to provide a very flexible means of calibration or linearization of the sensor; but in the future probably the most important aspect of the integral microcomputer is that it will free the sensor designer from certain constraints which have always plagued instrument development. I am referring in particular to the effect upon the sensor of parameters other than the one whose measurement is desired. In the past it has been necessary to design sensors to be as insensitive as possible to such cross parameters; however, the smart sensor can utilize the microcomputer to measure the offending parameter and to correct computationally for its influence on the sensor

*The origin of the expression "smart sensor" is somewhat uncertain. By 1979 it had gained enough currency in the USA for the National Bureau of Standards to organize a workshop with this title. It may have become popular in reaction to the rather pompous expression "intelligent instrument" which started to be applied to computer-controlled analytical instruments in the early 1970's.