Leonardo da Vinci
Education and Culture

Modular Courses on Modern Sensors
Leonardo da Vinci project CZ/00/B/F/PP-134026

Master Book on Sensors

editors: P. Ripka and A. Tipek

Part A

Part B

2003

Introduction and Acknowledgments

This book is a final product of Leonardo pilot project "Modular Courses on Modern Sensors" (CZ/PP-134026). More about the project can be found at **http://sensor.feld.cvut.cz/leonardo**.

Although it was not originally planned, it turned out that creating a printed textbook is reasonable and desired by the project participants and numerous other teachers and instructors.

The first version of the "Master Modules" was created by project partners in 2001 and served as a source material for production of the national educational texts in 8 languages. All modules were reviewed by independent experts and evaluated by the whole partnership.

Second version of Master modules was created in early 2003. It contains large revisions and improvements.

This book represents a final version of Master texts.

From the beginning the modules were intended to create self-consistence unit. This brought some redundancy – we hope that the readers will tolerate some overlaps.

We would like to thank all the authors for their hard work.

We also thank to all reviewers, correctors and experts who contributed to improving the quality of this book.

The text was examined and approved by Skoda Auto, which enabled its creation by their generous support.

The field of sensors is extremely wide and one book can never cover it completely. The editors and module authors would appreciate any feedback from the readers.

Prague, October 30, 2003

Pavel Ripka and Alois Tipek
the editors.

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MASTER MODULE 1

PRESSURE SENSORS

Written by Dr André Migeon and Dr Anne-Elisabeth Lenel, M2A Technologies Sarl (France)

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Preface

Like temperature and terrestrial gravity, pressure is one of the physical quantities most often considered in our environment. It actually governs the majority of natural phenomena and physics which surround us. This situation has obvious extensions at the industrial level.

That is why pressure measurement is an historical concern which has led to multiple inventions and a wide line of sensors.

Accordingly pressure is a significant parameter in such varied disciplines as in thermodynamics, aerodynamics, acoustics, fluid mechanics, soil mechanics, biophysics, etc.

The Master Module entitled PRESSURE SENSORS explains the different principles now known and their advantages and limits for industrial uses.

Acknowledgments

This project was carried through with support from the European Community. The content of this project does not necessarily reflect the position of the European Community or the National Agency, nor does it involve any responsibility on their part.

1.1 Introduction

If we consider industrial applications specifically involving problems of pressure measurement, we will see immediately that Power Engineering consumes most of the pressure sensors produced. This is obvious because the hydraulic, thermal, nuclear and other installations generating mechanical, thermal or electrical energy require the constant monitoring and control of pressures: overpressure could cause the deterioration of enclosures or drains and cause very significant damage.

As a significant parameter, pressure enters into the control and operation of manufacturing units, automated or operated by human operators. Its measurement is also used in robotics, either directly in controls, or indirectly as a substitute for touch (artificial skin for example), for pattern recognition or for determining strength of grip.

All these activities require instrument chains in which the first link is the pressure sensor, delivering data relating to the pressure of compressed air, gas, vapour, oil or other fluids, determining the correct operation of machines, mechanisms or systems governing the course of a process.

The variety of expressed needs demands a great diversity of sensors. This diversity also derives from the fact that the physical quantity “pressure” covers a very wide field from ultra-high vacuums to ultra-high pressures. It can be expressed as an absolute value (compared to vacuum) or as a relative value (compared to atmospheric pressure); it can also represent a difference between two pressures or relate to various media and fluids whose physical characteristics (e.g. temperature) or chemical characteristics (e.g. risk of corrosion) are very varied.

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MASTER MODULE 2

OPTICAL SENSORS

Written by Stanislav Ďaďo and Jan Fischer, Czech Technical University, Prague

Contents

2.0 Introduction

Optical sensors are measuring devices in which a measured quantity is converted to an optical, and subsequently, an electrical signal by means of an optoelectronic transducer ([10]). Optical sensors belong to the class of contactless methods of measurement eliminating backward influence of a measuring device on an object of measurement.

Here the optical quantity is described as any quantity characterising or influencing the generation and/or propagation of electromagnetic waves with a spectrum corresponding to visible and near infrared light. In order to gain a proper insight into processes taking place in optical sensors a brief review of the basic properties of light, optical components and optoelectronic devices will be introduced.

Based on this theoretical background the behaviour and properties of typical optical sensors for the measurement of various physical quantities will be described. The main attention will be devoted to the optical part of a sensors structure. The reason for this approach is the fact, that the output signals from optical sensors are of an electronic nature and the methods of their further conditioning and processing are generally known from electrical measurement and usually do not represent the sensor's specific problem.

MASTER MODULE 3

FLOW SENSORS

Written by R. Meylaers, F. Peeters, M. Peetermans, KHK Belgium

Contents

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Preface

You are a producer of soft drinks and you want to know at any point how many liters per hour you produce. Or your company discharges waste water on which taxes are levied per liter. These are only two everyday examples in which flow measurement plays an important part. The thousands of applications of flow meters tell us that they are one of the most important industrial measurements. We attempt to give you an idea of the different principles that are used and of the characteristics and properties of each method.

3.1 Introduction

Measuring the flow of liquids, gases, vapour or solids is an important necessity both for the processing industry and for occasional readings. In some processes inaccurate flow-rate measurement is so important that it can make the difference between profit and loss. In other cases inaccurate or erroneous flow measurements can have serious or even disastrous consequences.

MASTER MODULE 4

SENSOR BUSES, INTELLIGENT SENSORS

Written by Jaime Arévalo Caicedo, Francesc Sabaté i Domènech, Vincenc Rius Moreno and Jordi Ojeda i Rodríguez ICT Barcelona, Spain

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4.1. Introduction to Intelligent Sensors

Sensor technologies are evolving continuously in order to improve parameters such as sensitivity, selectivity, range of substance detectable, and applicability of sensors in dynamic and complex enviroments.

However, industry demands new additional characteristics of those sensor devices: flexibility, openness and adaptability to users, and control systems. First of all, the signal sampling can be taken at any location and it must be received accurately; secondly the user has to be able to program or store the reading in particular formats; and finally a local interface may be required.

A sensor must do something more than just produce an accurate measurement in order to be considered "intelligent".

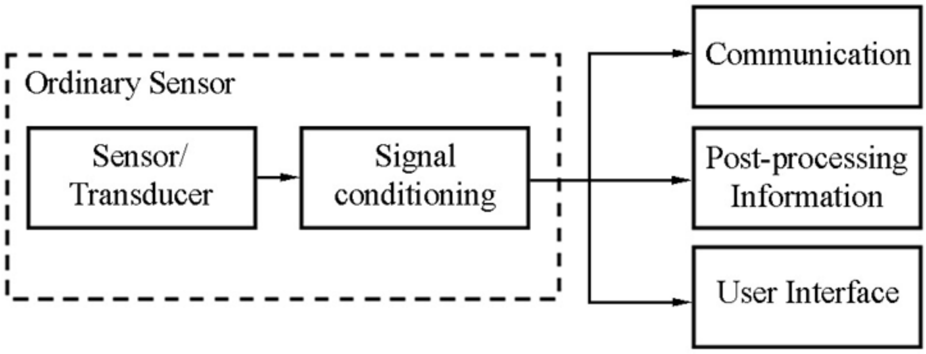

Figure 4.1 Intelligent sensor structure

Sensor innovation is embedding new functions in the same device. An intelligent sensor is an ordinary sensor, which has additional qualities: communications, user interface, functions and computational abilities (See Figure 4.1).

Nowadays control systems are distributed and I/O can be far from control device. Therefore sensor information has to be sent rapidly, securely and accurately to control system; for this case, a communication bus is required.

Intelligent sensors permit configuration of calibration curves, scales, alarm events, diagnostic parameters, etc., in order to adjust them to the user specific process requirements. Sometimes the user also may wish to reprogram the sensor by means of utility software provided by the manufacturer. Thus, an important component is the user interface that provides the means and the necessary information that allow adjustment in field and programming.

It may be useful for these devices to have executable capabilities, for mathematical computation, statistical analysis, system modification or data logging. Consequently a post-processor component would be required. These abilities are important in order to perform some intelligent features like self-calibration, auto diagnostics, temperature compensation, for instance.

Thus an intelligent sensor is the result of combining different technologies. These technologies will be outlined in this module.

MASTER MODULE 5

ACCELEROMETERS AND INCLINOMETERS

Written by Dr André Migeon and Dr Anne-Elisabeth Lenel, M2A Technologies Sarl (France)

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Preface

Accelerometers have existed for several decades and they are always in constant evolution because they influence in a strategic way the performances of the devices which use them. In the past fifteen last years in particular, thanks to optics and micro technologies, there was enormous progress with precision, linearity, stability and also bulkiness and electric consumption of the sensors.

According to mechanics fundamental principles, acceleration corresponds to the relationship between a force and a mass. The accelerometers use principles based on a physical phenomenon which allows, starting from this relationship, to obtain an electric signal. The accelerometers can use physical phenomenon which makes a direct measurement of a force (piezoelectric sensor, sensor with balance of force), or an indirect measurement, by the means of the displacement or the deformation of a sensing element.
We can classify these sensors by referring to the phenomena they are intended to analyze. Then, the useful frequency band of these phenomena determines the type of suitable sensor, taking into account the required precision.

There is a great diversity of applications of accelerometers in various fields like automotive areas, aeronautics, instrumentation, medical devices and automation. We will limit this module to the presentation of relevant physical principles and their associated technologies, and we will present some examples of applications.

Acknowledgments

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5.1 Introduction

The term " accelerometer "covers two types of device:

➔ linear accelerometers

➔ angular accelerometers

By familiarity, the experts in the " inertia " discipline use the term " accelerometer " only to define linear accelerometers. The latter are devices designed to measure the specific non-gravitational force affecting their seismic mass.

Accelerometers cannot measure the absolute acceleration of a moving object. Indeed, it is necessary simultaneously to know the value of the local field of gravitation and the value of the accelerometer reading to determine the acceleration affecting a moving object, except in the particular case of a movement which absolute acceleration is zero.

Acceleration corresponds, according to the fundamental principles of mechanics, to a relationship between a force and a mass. All the acceleration sensors draw on a physical phenomenon which, starting from this relationship obtains an electric quantity or some displayable information for the operator.

Acceleration sensors can be classified according to the physical principle they use:

➔ a direct measurement of a force (piezoelectric sensor, sensor with balance of couple or forces),

➔ or an indirect measurement, by means of displacement or deformation of a sensing element.

We can also classify these sensors by referring to the phenomena they are intended to analyze. Then, the useful frequency band of these phenomena determines the type of suitable sensor taking into account the required precision.

This module will highlight the fundamentals necessary to understand what an accelerometer is and how to choose the right one for a specific need. The advantages and disadvantages of the different types of accelerometers will be discussed to reveal the industrial relevance of these sensors.

MASTER MODULE 6

CHEMICAL SENSORS AND BIOSENSORS

ver.1.5

Edited by Gillian McMahon

National Centre for Sensor Research, Dublin City University, Ireland.

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PREFACE

My sincere thanks go to the following people who contributed to this master module and without whom it would not have been possible for me to create this text: Dermot Diamond, Kieran Nolan and Paddy Kane for the introduction (chapter 1) and chapter 2 on 'What is involved in developing a sensor?', Robert Forster, Margaret Sequeira and Kim Lau for much of the large chapter 3 on electrochemical sensors, Brendan Duffy for chapter 5 on acoustic sensors, Richard O'Kennedy, Tony Killard and Paul Dillon for writing chapter 6 on biosensors and for their contributions to chapter 9 on applications i.e. the section on biomedical applications and the subsection on environmental biosensors, Edel Minogue, Kim Lau and Rod Shepherd for chapter 7 on fabrication of sensors, Greg Hughes for providing chapter 8 on surface characterisation, Gwenaelle LeGurun for providing most of the section on environmental applications in chapter 9, June Frisby for the section on food applications in the same chapter, Michaela Bowden and Brett Paull for writing the section entitled microanalytical instruments as sensors in chapter 10, Aogan Lynch for the section on solid-state sensor arrays and finally Robert Forster for the section on sub-micron dimensioned sensors, also in chapter 10.

6.1 Introduction

The world in which we live is rapidly becoming dominated by digital information. Initially, the digital revolution primarily involved stand-alone computers that gradually became networked. More recently, the merging of computing with wireless communications systems has led to an enormous growth in accessibility to, and hence demand for, this information. At present, this demand is dominated by a mixture of text, audio and image-based data driven mainly by almost ubiquitous accessibility to the internet. However, the communications 'web' that has been assembled over the past decade will fuel demand for more sources of information and data about important aspects of our lives - our health, our environment, our food, our work. Sensors provide portals between the 'real' or analogue world in which we live, and the digital world of computers and modern communications systems. They make it possible for us to obtain real time information about things we can see, touch, smell and hear, and about other things that we cannot detect - things that can be harmful or beneficial to us.

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MASTER MODULE 7

LEVEL, POSITION AND DISTANCE

Written by G. Hartung, Berufsfortbildungswerk, Heidelberg, Germany

Content

7.1 Introduction

7.1.1 Classification of LPD sensors

Measuring the level, position, distance and displacement of physical objects is essential for many applications: process feedback control, performance evaluation, transport, traffic control, robotics, security systems - just to name a few.

Position means determining the object's co-ordinates (linear or angular) with respect to a selected reference point.

Displacement means moving from one position to another for a specific *distance* or angle. A critical distance is measured by *proximity* sensors, which are in fact a threshold version of a position sensor. A position sensor is a linear device whose output signal represents the distance to the object from a reference point.

The range of distance measurement varies according to the application from fraction of µm to several hundreds of meters.

The requirements for precision of measurement may also vary over a wide range from task to task and are usually selected as a compromise between required precision and cost of production or maintenance of the sensor. For high precision sensor the influences of external variables such as ambient temperature, pollution, humidity, pressure and radiation have to be taken into account.

There are many possibilities for the operating principles of LPD sensors. Theoretically all physical phenomena in which distance, position or displacement influences some electrical quantity can be used as a concept for sensor construction.

With regard to physical principle of operation the following types of LPD sensors are available:

- mechanical,
- electrical,
- magnetic,
- optical,
- acoustic.

Another very important criterion for LPD sensor classification is the *mutual interaction* of the sensor and the measured object. The sensors that can accurately operate only when they are in direct contact with measured object belong to the class of *contact* sensors. By analogy, sensors, which perform the measurement task without direct contact with a measured object, form the class of *non-contact* sensors. Obviously the non-contact sensors offer many advantages as ideally they do not interfere with the measured object. Unfortunately many of measurement tasks cannot be fulfilled by non-contact sensors, nevertheless in measurement theory and practice there is a permanent thrust for finding new principles for non-contact sensors.

For the selection of the sensor systems suitable for the given measurement task, the following aspects should be considered as important criteria:

- measurement range,
- measurement precision,
- resolution,
- accuracy of repeatability,
- linearity,

as well as drift, offset, and change of the sensitivity due to temperature, ageing, pressure, etc.

For measurement of time varying quantities (e.g. oscillatory change of position - vibrations) the dynamic properties of sensors are often the key criterions for selection. The dynamic properties of sensors are determined by the *frequency response* of the sensor defined as the ratio of the amplitudes of output and input variables with sinusoidal waveform at the different frequencies.

MASTER MODULE 8

TEMPERATURE SENSORS

Written by F. Peeters, M. Peetermans KHK Belgium
Production: L.Indesteege, VIA, Belgium

Contents:

Preface

Drawing a good glass of beer, pasteurizing milk or producing electricity are all processes that require accurate temperature measurement. There exist various methods to perform the measurement, each with its own characteristics and possibilities. In this module, we will familiarize you with the world of industrial temperature measurement.

Introduction

In the first part of this course, concepts that are commonly used in thermal measuring techniques are explained. We start with a definition of heat and temperature and then give different methods to read temperature. The necessity of a thermal equilibrium will be demonstrated with an example. It is important to meticulously execute the measurements.

The second part deals with physical and direct ways to measure temperature: glass thermometer, liquid filled thermometer, liquid filled expansion thermometer, pressure temperature detector, vapour-pressure temperature detector and bimetallic thermometer.

These five possible ways to measure temperature are followed by measuring principles, the construction and application of sensors such as thermocouples, resistance temperature detectors (RTDs) and monolithic temperature measurement.

In the last part we find among other things the practical possibilities for pyrometry. The basic concepts of electromagnetic radiation and the execution and construction of pyrometers give us an idea of this technique that is blooming now, partly due to computer technology.

MASTER MODULE 9

SOLID-STATE GYROSCOPES AND NAVIGATION

Written by Dr André Migeon and Dr Anne-Elisabeth Lenel, M2A Technologies Sarl (France)

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9.1 Introduction

It was at the beginning of the 20th century that radioelectric navigation made its appearance. These methods of radio navigation have made it possible for the enormous progress in the positioning and nautical field. The dead reckoning, the compass and the log of use had received for centuries until a few decades ago, only the help of the gyroscopic compass. But the gyroscope itself represents the type of progress to come. Indeed, the capacity of a top animated by a fast rotational movement, to preserve a fixed direction in space had been recognised in the 19th century. The first practical experiment was carried out in 1865, thanks to the maintenance of the movement by an electric motor. The first gyrocompass was patented by Dr. Anschutz in 1904, and embarked upon in 1908, thanks to the adjustment of a pendule/gyroscope unit, which freed the system from rolling of the ship.

Consequently, the question arises of having autonomous systems for navigation: since acceleration is the only measurable physical quantity without an external reference and, therefore, is usable by an autonomous system, there is a natural association between accelerometers and gyrometers.

The accelerometers and the gyrometers have existed for several decades. They are constantly evolving because they condition the performance carriers (see the effectiveness), which use them in strategic way. In the last fifteen years in particular, thanks to optical and to micro-technologies, there has been enormous progress made in precision, linearity, stability as well as in obstruction and electric consumption of these sensors.

Inertial navigation has evolved continuously throughout the last decades: the first combined accelerometer and gyroscope was produced in 1923; the first platform with three axes in 1924; the first operational equipment was launched in 1940s on the rockets V2, and the first power station tested in flight in France was in 1961.

The gyrometers intended for inertial navigation must satisfy particular requirements such as very good precision, good linearity and a correctly adapted bandwidth.

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The gyrometers must be able to detect revolution speed varying from continuous to 100°/s. They must also be of good manufacturing quality. For example a shift of 2 nm between the centre of gravity and the centre of pressure of Archimedes can produce a sufficient unbalance in gyrometer to create a drift of 10^{-9} degree per hour.

The lowest possible drift is desirable in a gyrometer.

For a ship, whose navigation can last several weeks, errors can accumulate with time, and a periodic correction is required.

In comparison, for a plane whose flight lasts only a few hours, or a missile where the duration of flight is measured in minutes, the accumulated errors remain acceptable.

In the standard case, a gyroscope has drifts of 10^{-2} degree per hour where errors are incurred at 1 mile per hour.

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MASTER MODULE 10

MAGNETIC SENSORS

Written by S. Ripka and P. Ripka

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Magnetic sensors are used in applications everywhere: from home appliances to cars and industry and scientific instruments. They either sense magnetic field itself, or more often, another physical variable which is transformed into a magnetic response. Magnetic sensors are reliable, they have a large operating temperature range and they are resistant to vibrations, dirt and interference. More detailed information on magnetic sensors can be found in general sensor books [1-3] and in specialised literature [4-6].

MASTER MODULE 11

NEW TECHNOLOGIES AND MATERIALS

Written by A. Tipek and P. Ripka, Czech Technical University
and E. Hulicius, Institute of Physics, AVCR
with contribution from A. Hospodková and P. Neužil

Contents:

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11.1. Introduction - MEMS

MEMS is an abbreviation for "Micro-Electro-Mechanical Systems" or very small electrical / mechanical devices [1]. They feature the integration of mechanical elements, sensors, actuators and operating electronics on a common silicon substrate with the use of microfabrication technology [2].

While the electronics (used as processors) are fabricated using integrated circuit process sequences (CMOS, BiPolar or BiCMOS processes), the micromachining processes selectively etch away parts of the silicon wafer or add new structural layers to form the required mechanical and electromechanical devices [3].

Microelectronic integrated circuits (ICs) can be regarded as the "brains" of systems and MEMS augments their decision-making capability with "eyes" and "arms", to allow microsystems to sense and control the environment.

Components of MEMS :

- MicroSensors
- MicroActuators
- MicroElectronics
- MicroStructures

Since MEMS devices are manufactured by the help of batch fabrication techniques, similar to ICs, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost. With thin films, the photolithographic fabrication procedures make it possible to build extremely small, high precision mechanical structures using the same processes that have been developed for electronic circuits [4].

MEMS promises to revolutionise nearly every product category by bringing together silicon-based microelectronics with micromachining technology, thereby making possible the realisation of a complete system-on-a-chip [5].

MEMS technology is enabling new discoveries in science and engineering such as the Polymerase Chain Reaction (PCR) microsystems for DNA amplification and identification, introducing new technologies as in the micromachined Atomic Force Microscopes (AFM), Scanning Processing Microscopes (SPM) and Scanning Tunnelling Microscopes (STM), biochips for detection of hazardous chemical and biological agents, and microsystems for high-throughput drug screening and selection.

Examples of MEMS devices, which we meet everyday, are inkjet-printer cartridges, accelerometers that deploy car airbags and miniature robots [6].

The successful production of MEMS needs the development of appropriate fabrication processes in four major areas

- micromachining
- microfabrication
- micromechanics
- microelectronics

The conventional silicon planar microelectronics technology has been adapted to the processing of both passive and active components. The passive material is one that does not play an essential role in the sensing mechanism (e.g. SiO_2 insulating layer in a pressure sensor) in contrast to an active material, which does (e.g. metal oxide layer in a chemical sensor).

The basic MEMS processes are:

IC Processes

- oxidation
- diffusion
- LPCVD (low-pressure chemical vapour deposition)
- Photolithography
- Epitaxy
- Sputtering
- etc.

Micromachining Processes

- Bulk Micromachining
- Surface Micromachining
- Wafer Bonding
- Deep Silicon RIE (reactive ion etching)
- LIGA (lithography, electroforming, moulding)
- Micromoulding
- etc.

MEMS devices are extremely small (e.g. electrically driven motors are smaller than the diameter of a human hair), but MEMS technology is not only characterised by the size [3].

Also, MEMS do not only include products based on silicon, even though silicon possesses excellent material properties (e.g. the strength-to-weight ratio for silicon is higher than for many other engineering materials). MEMS is a manufacturing technology; a new way of making complex electromechanical systems using batch fabrication techniques similar to the integrated circuits [7].

MEMS has several advantages:

Imagine classical sensor-actuator-electronic systems, in which the sensors and actuators are the most costly and unreliable parts. In comparison, the MEMS technique allows these complex electromechanical systems to be manufactured using batch fabrication techniques and therefore leading to a distinct decrease in the cost with increased reliability [8].

One example of the advantages of MEMS is the accelerometers for crash air-bag deployment systems in automobiles. The conventional system uses bulky accelerometers made of discrete components mounted in the front of the car with the separate electronics near the air bag and costs over $50. MEMS have made it possible to integrate the accelerometer and electronics onto a single silicon chip at a cost of $5 to $10. These MEMS accelerometers are much smaller, more functional, lighter, and more reliable [3].

The microsensors produced using the silicon process have been developed since 1980. Circuits for preamplifier and logic elements have been integrated with transducers and used to make an intelligent chip element, called an intelligent sensor or smart sensor. Microsensors with moveable parts have been developed since 1985 and have become the first applications of micromechanical parts in the industrial field.

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CTU – Czech Technical University in Prague
Zikova 4
166 36 Praha 6
Czech Republic
http://www.cvut.cz

bfw – Berufsfortbildungswerk des DGB
Rohrbacher Str. 102
69126 Heidelberg
Germany
http://www.bfw.de

DCU – Dublin City University
Dublin 9
Ireland
http://www.dcu.ie

ICT – Institut Catalá de Tecnologia
Ciudad de Granada 131
08018 Barcelona
Spain
http://www.ictnet.es

IDEC S.A.
96, Iroon Polytechniou Ave
185 36 Piraeus
Greece
http://www.idec.gr

M2A Technologies
46, rue Luis Barthou
26000 Valence
France
http://www.m2atechnologies.com

SKODA AUTO a.s.
V. Klementa 869
293 60 Mladá Boleslav
Czech Republic
http://www.skoda-auto.cz

VIA – Vervolmakingscentrum voor Industrieel-technische Applicaties
Universitaire Campus Gebouw B5
3590 Diepenbeek
Belgium
http://www.via-opleidingen.be

ZSE – Zespol Szkol Elektronicznych
120, ul. Hetmanska
35 – 078 Rzeszow
Poland
http://zse.ircnet.pl