

## INTEGRATION OF MARIE CURIE CHAIRS (EXC) PROJECT BASED COURSE ON 'SMART SENSORS SYSTEMS DESIGN' INTO 'SENSORS AND SIGNAL CONDITIONING' CURRICULA

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**Abstract:** This paper describes a successful approach of integration of Marie Curie Chairs (EXC) project based course on 'Smart Sensors Systems Design' into the current curricula in 'Sensors and Signal Conditioning' at Technical University of Catalonia (UPC-Barcelona, Electronic Engineering Department) for graduate and postgraduate students. It is strongly connected with new research results obtained during the SMARTSES project in this emerging field. The course main objectives, contents, teaching methodology, laboratory activities and qualification criteria are discussed.

**Keywords:** smart sensors, signal conditioning, curricula

### 1. INTRODUCTION

Marie Curie Chairs are one out of three actions funded under the EU's Sixth Framework Programme for Research and Technological Development (FP6) and devoted to the promotion and recognition of scientific excellence created to increase the visibility and attractiveness of European research. Like the other excellence actions, the Marie Curie Chairs (EXC) promotes the dissemination of research results for the benefit of the scientific community. In order to achieve this aim the action is strongly focused on different teaching activities correspond to directions in research, which are relevant for Europe. It means lectures, research courses and special training events to students at graduate and/or postgraduate levels, engineers and researchers on the basis of latest research results taking a multi-disciplinary approach and using innovative teaching methods and new technologies to benefit students from a wider range of European institutions [1, 2].

Smart sensor systems researches are highly relevant to European research achievements and interests. As European integrated circuit manufacturers continue to improve micro-electro-mechanical systems (MEMS), the demand will rise for smart sensors, which are created by combining traditional sensor and microchip or system-on-chip technologies.

In the frame of Marie Curie Chairs (EXC) project MEXT-CT-2005-023991 SMARTSES the new course on 'Smart Sensors Systems Design' [3] was created and integrated into the current curricula in 'Sensors and Signal

Conditioning' at Technical University of Catalonia (UPC-Barcelona, Electronic Engineering Department) for graduate and postgraduate students. It is strongly connected with new research results obtained during the project in this emerging field. The subject to be taught is of a leading edge, has a multidisciplinary nature, and corresponds to directions in research, which are relevant for Europe.

### 2. COURSE CONTENTS

The general objectives of six credits 'Sensors and Signal Conditioning' [4] course are: to study of sensors operation, properties and limitations; specific interface design for amplitude and frequency-time output sensors; and their applications. The basic contents of the course includes sensors, sensor signal conditioning, analog and mixed-mode signal processing, data acquisition, calibration techniques, smart sensors interface protocols. The course covers the following main topics:

1. Introduction to sensor-based measuring systems. Primary sensors (2 hours):
  - 1.1. General concepts
  - 1.2. General input-output configuration
  - 1.3. Static and dynamic characteristics
  - 1.4. Generalized input impedance
  - 1.5. Primary sensors
2. Sensors with electrical output (4 hours):
  - 2.1. Variable resistance sensors
  - 2.2. Reactive and electromagnetic sensors
  - 2.3. Generating sensors
3. Conditioning circuits for sensors. Amplitude measurement approach (8 hours):
  - 3.1 DC linear conditioning circuits for resistive sensors
  - 3.2 AC linear conditioning circuits for resistive and reactive sensors
  - 3.3 Low drift conditioning circuits for generating sensors

4. Conditioning circuits for sensors. Frequency-time conversion approach (14 hours):

- 4.1 Quasi-digital sensors state-of-the-art
- 4.2 Time and frequency based sensor conditioning techniques. Direct sensor-to-microcontroller interface
- 4.3 Sensor interface chips and integrated frequency-to-digital converters
- 4.4 Digital and smart sensors
- 4.5 Smart sensors systems design
- 4.6 IEEE 1451 standard for smart sensors and its extension for quasi-digital sensors and transducers.

3. TEACHING METHODOLOGY, LABORATORY ACTIVITIES AND MATERIALS

The teaching methodology includes lectures, problem solving, guided laboratory activities (six 2-4 hour labs) and Project Based Learning (PBL) on ‘Data Acquisition and Smart System Design for Quasi-Digital Sensors’. The course for PhD students can also include so-called training-through-research using a special equipment and remote laboratory for graduate and postgraduate students.

3.1 Laboratory activities

During the course the following laboratory activities are planned:

- Lab 1. Characterization of a sensor-based measurement system (2 hours);
- Lab 2. Scale based on a load cell and an instrumentation amplifier (4 hours);
- Lab 3. Thermistor based thermometer. Analog and numerical linearization (4 hours);
- Lab 4. Capacitive sensor conditioning. Non-coherent and coherent amplitude detection (4 hours);
- Lab 5. Universal frequency-to-digital converter: quartz-accurate automated calibration technique (2 hours);
- Lab 6. Time and frequency sensor conditioning: smart data acquisition system for quasi-digital sensors. (2 hours).

The Labs No. 5 and 6 are based on the integrated, two-channel, high precision, multifunctional, universal frequency-to-digital converters designed before (UFDC-1, Fig. 1) and during the Marie Curie Chairs (EXC) project SMARTSES (UFDC-1M-16) respectively [5, 6]. Universal frequency-to-digital converters UFDC-1 and UFDC-1M-16 are complex fully digital CMOS integrated circuits based on novel patented methods for frequency, period, its ratio, duty-cycle and phase-shift measurements [7-10].

Such integrated circuits are well suited practically for any quasi-digital sensors and transducers to provide a sensor interfacing and signal conditioning because offer high performances with flexibility and requires a minimum of external components. These CMOS converters have one generating mode (8 MHz rectangular pulses) and 16 measuring modes for any frequency-time parameters of electric signals: frequency, period, its difference and ratio, duty-cycle, duty-off factor, time interval between start- and

stop-pulse, PWM, pulse width and space, phase-shift and pulse number.

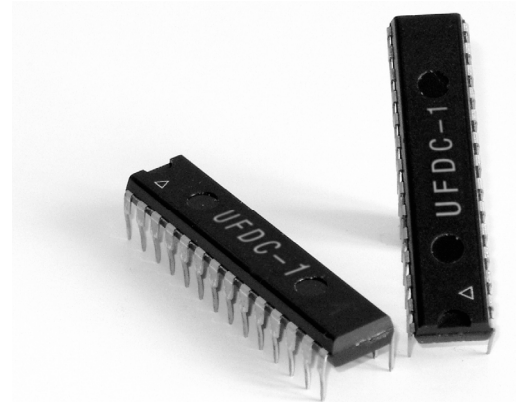


Fig. 1. Universal Frequency-to-Digital Converters (UFDC-1)

In addition the ICs can measure directly a rotation speed. The converters have programmable relative error from 1 to 0.001 %, scalable resolution, non-redundant conversion time (significantly reduced in the UFDC-1M-16 chip version) and a wide frequency range from 0.05 Hz to 7.5 MHz (120 MHz with prescaling). Both integrated circuits are available in 28-lead Plastic Dual Inline Package (PDIP, Fig. 1) and compact 32-lead TQFP package.

It supports three popular serial interfaces such as two direction RS-232 (master and slave communication modes, Fig. 2 a, b), 2-wire I<sup>2</sup>C (Fig. 3) and 3-wire SPI compatible (Fig. 4) [11].

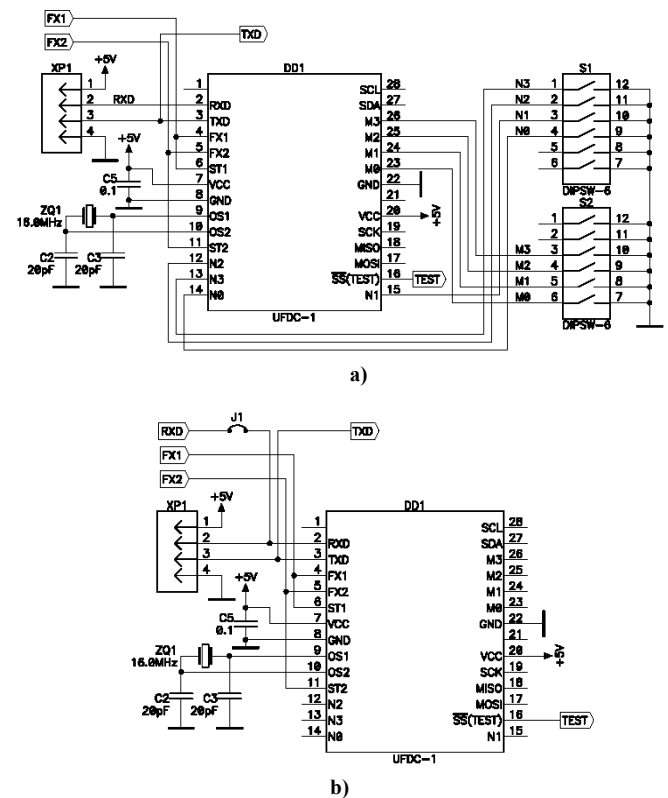


Fig.2. Circuit diagram for the UFDC-1 working in autonomous master (a) and slave (b) modes according to RS-232 interface.



UFDC-1. The reason of this laboratory activity is the following.

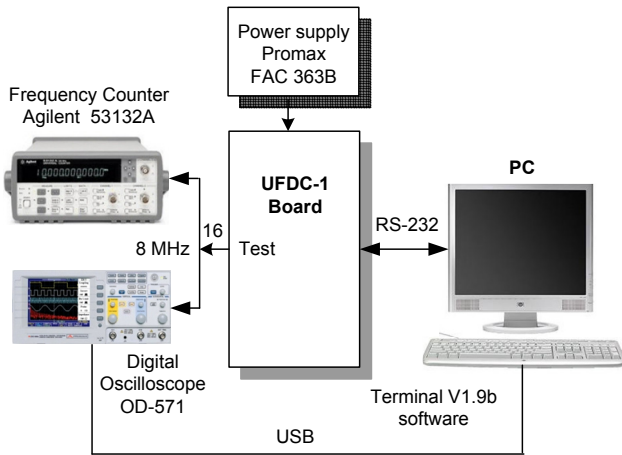


Fig.8 Measurement set up for Lab. 5 on “Quartz-Accurate Automated Calibration Technique”

The frequency variation due to an adjustment inaccuracy for a room temperature crystal oscillator (RTXO) can exceed 30 ppm (or 0.003 %) and has a systematic character. For example, 16 MHz crystal oscillator from *Siward* with 30 ppm determined tolerance has the real frequency 16 001 400 Hz that corresponds to 90 ppm (0.009 %) reference error. In order to use the UFDC-1 with low cost crystal oscillators for conversions with the quantization error better than 0.01 % it is expediently to make a calibration with the aim to compensate the adjustment or trimming inaccuracy of quartz oscillator [13]. During this laboratory activity students must determine if the calibration procedure is necessary for the SDE 16 MHz quartz oscillator that is using in the UFDC-1 board and make the calibration procedure according to the UFDC-1 specification and application note [11]. It is the following:

- 1) The test command "T" toggles the UFDC-1 in the calibration mode. The sequence of rectangular pulses with frequency  $f_{osc}/2$  ( $16/2 = 8$  MHz) is generated on its TEST output (pin 16).
- 2) The frequency of this pulse sequence should be measured with the help of frequency counter, for example, Agilent 53132A with the relative error not worse than 0.0001 % or, at least, 0.0003 %.
- 3) The fractional part of measuring result is rejected and the number 8 000 000 (Hz) should be subtracted from the integer part.
- 4) The received correction factor  $\Delta$  need to be converted into the hexadecimal number.
- 5) The command "F  $\pm \Delta$ " (with taking into account the result sign) puts the correction value into the UFDC-1. The command "F" without parameters indicates the internal value of correction factor and can be used for checking the loaded number.

The calibration is performed only once. The correction factor  $\Delta$  is stored in the nonvolatile memory of the UFDC-1, which holds this value after power-off.

The measurement set up for Lab. 6 on “Time and frequency sensor conditioning: smart data acquisition system for quasi-digital sensors” is shown in Fig. 9.

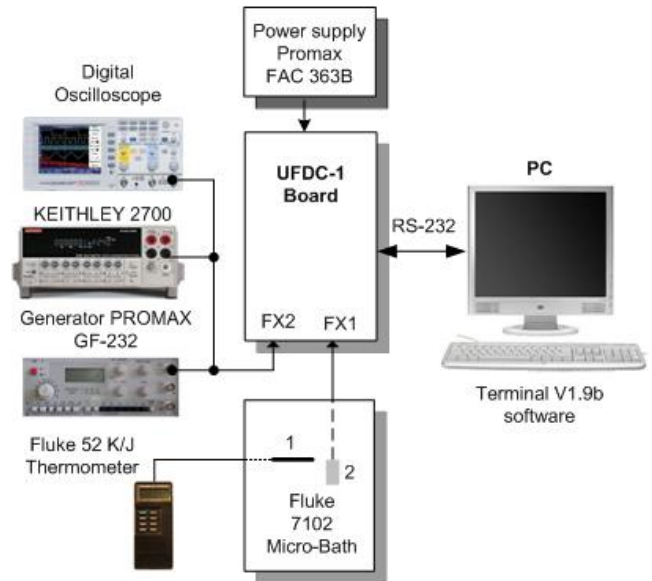


Fig.9 Measurement set up for Lab. 6 on “Time and frequency sensor conditioning: smart data acquisition system for quasi-digital sensors” (1- semiconductor temperature quasi-digital sensor; 2- thermocouple)

In this laboratory activity students make some metrological experiments with different quasi-digital sensors, for example, semiconductor temperature sensors with frequency (MAX 6577), period (MAX 6576), duty-cycle (SMT-160-30) and pulse-width modulated (MAX 6673) outputs. Main metrological performances of these temperature sensors are shown in Table 1.

Table 1. Main metrological performances of quasi-digital temperature sensors

Sensor Parameter	MAX 6577	MAX 6576	MAX 6673	SMT-160-30
Manufacturers	Maxim	Maxim	Maxim	Smartec
Temperature range, °C	- 40 ... + 125	- 40 ... + 125	- 40 ... + 125	- 45 ... + 130
Max. temp. error, °C	± 3.0	± 3.0	± 3.0	± 1.7
Output	Frequency 14.57 ... 1592.6 Hz	Period 0.0023 ... 0.26 s	PWM 1.4 kHz	Duty-cycle 1...4 kHz

Interfacing boards for temperature sensors MAX 6577, MAX 6576 and MAX 6673 including semiconductor sensors in SC70 package, filter and connector are shown in Fig. 10.

During the metrological experiments a quasi-digital semiconductor temperature sensor should be connected to the first input (channel) of UFDC-1 boards and put into the Fluke 7102 Micro-bath with a temperature range  $- 5^{\circ}\text{C}$  to  $+ 125^{\circ}\text{C}$ . Appropriate relative error for the UFDC-1 and measuring mode should be chosen. The KEITHLEY 2700 digital multimeter with frequency (3 Hz to 500 kHz) and period (2  $\mu\text{s}$  to 333 ms) measuring functions (0.01 %



relative error) is used for sensors output signals measurements.

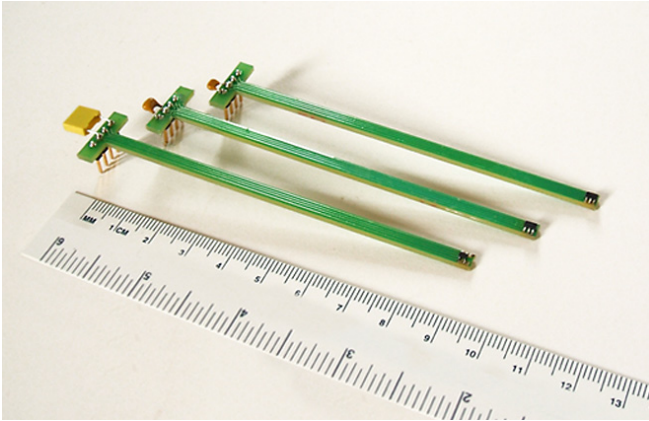


Fig. 10. Interfacing boards for temperature sensors

The digital oscilloscope is used for signal shape monitoring at sensors' outputs. The temperature in Fluke 7102 Micro-bath is monitored by the Fluke 52 K/J thermometer with measurement accuracy  $\pm (0.1\% \text{ of reading} + 0.7^\circ\text{C})$ .

Taking into account multifunction possibilities of UFDC-1 the PWM signal at MAX 6673 sensor's output can be measured by two ways. The first one means simple measurements for pulse width  $t_p$  and pulse space  $t_s$  with the further calculation of temperature according to appropriate equation [14]. The second way means period measurements  $T_x$ , then the measurements  $t_p$  or  $t_s$  with the further calculation for  $t_p = T_x - t_s$  or  $t_s = T_x - t_p$ . Such method lets increase accuracy in the case when  $t_p$  or  $t_s$  is very narrow.

During the laboratory activities any quasi-digital sensors or transducers with frequency, period, duty-cycle, PWM, pulse number or phase-shift output can be directly connected to the UFDC-1 board. In addition, the PROMAX GF-232 functional generator is used for different sensors output emulation and can be connected to the second UFDC-1 board input at the same time.

Students should make at least 60 measurements in each of point from the investigated temperature range and use statistics for determination of appropriate performances.

Due to serial interfaces RS-232 and SPI the UFDC-1 and UFDC-1M-16 integrated circuits can be easily integrated into the existent modular laboratory platform. The platform is based on a set of printed circuit boards. As usually each laboratory activity is implemented on a separate application circuit board that is connected to motherboard from which power supply, analog, digital inputs and outputs and some of the adjustments are provided. There are two versions of the motherboard. An Analog, intended for in-class laboratory activities with manual adjustments and mixed-mode Microcontroller-based, which includes ADC and DAC converters and embedded controller that provides TCP-IP access to the acquired signals. This board can be used in some of in-class activities and in all remote activities.

Documentation about schematics, board layouts, sensors and active components specification is provided through Virtual Campus in separate documents.

The references [15, 16] were selected as the basic and [17, 18] were recommended as complimentary references. In addition, a monthly up-dated Sensors Web Portal devoted to quasi-digital and intelligent sensors can be also recommended [19].

### 3.2 Project base learning and qualification criteria

The project-based learning is an active knowledge acquisition process that results from working with projects. It was used in the 'Sensors and Signal Conditioning' course related to its second part devoted to quasi-digital sensors, sensors systems and signal conditioning. In comparison with a classical teaching methodology the PBL means an active knowledge acquisition by all students; their autonomy, high responsibility and real results obtained during the project.

The PBL was realized by the following way. A class did divide into small groups. In the common case it should contain not more than 5 students. A manager among students should be chosen in each of group. Groups select problems, which are usually poorly defined. In case of the developed course it should be any sensors systems with some intelligent properties. At the beginning stage the project planning, information search, etc. should be executed. All groups are working on the concurrent basis. Project activities mean periodical reports, group discussions, progress estimation, etc. The final stage includes final groups' presentations, estimations (by both: students and professor), questionnaire, etc.

The following benefits are obtained due to the PBL approach:

- Students become more motivated by actively engaging in the learning process and taking responsibility for their own learning;
- The context of learning is more realistic;
- Graduates from PBL courses are better prepared for the workforce than those from more traditional programmes;
- They achieve higher levels of comprehension, develop more learning and knowledge-forming skills and more social skills as well;
- It reflects the way the mind actually works;
- This approach gives students immediate feedback. It keeps a constant flow going between teacher and student.

During the project based learning students create both: hardware and software for smart sensors systems and calculate its performances including the overall accuracy, (resulting error) based on an advanced engineering approach, which take into account a distribution laws for all components of error [20].

The qualification criteria for the course are: continuous assessment of laboratory activities and project (50 %), continuous assessment of problems (10 %) and final exam or project presentation (40 %). An online questionnaires prepared by EC was used to obtain a feedback from students. Each of students has received an International Frequency Sensor Association (IFSA) certificate.

#### 4. THE FUTURE COURSES

The future similar course as well as developed before 'Smart Sensors Systems Design' course will be based on new version of integrated Universal Frequency-to-Digital Converters: UFDC-2, its fast version UFDC-2M-20 [21] and Universal Sensors and Transducers Interface (USTI) [22], which were designed and developed during the SMARTSES project. New integrated converters have improved metrological performances (constant relative error up to 0.0005 %; extended frequency range up to 9 MHz without prescaling and 144 MHz with prescaling; non-redundant and reduced conversion time from 5  $\mu$ s), improved calibration procedure and extended functionality. So, the UFDC-2, UFDC-2M-20 and USTI have an addition measuring mode for relative and absolute frequency deviation measurements. The USTI has also a possibility for direct sensing elements (resistance, capacitance and resistive bridges) interfacing. In addition, these ICs let keep in its memory the TEDS according to IEEE 1451.4 standard [23] and can be used in analog-to-digital converters with intermediate voltage-to-frequency conversion [24].

The use of such integrated circuits in sensors related courses as 'Smart Sensors Systems Design', 'Sensors and Signal Conditioning', 'Data Acquisition and Signal Processing for Smart Sensors', 'Smart Sensors and MEMS' and others gives an unique opportunity to set up dozens laboratory activities based on a single universal integrated circuit.

#### 5. SUMMARY

The new course on 'Smart Sensors Systems Design' was created and successfully integrated into the current curricula in 'Sensors and Signal Conditioning' at Technical University of Catalonia (UPC-Barcelona, Department of Electronic Engineering), in the frame of Marie Curie Chairs (EXC) project MEXT-CT-2005-023991 SMARTSES. The course was given for the first time in the spring semester of 2008.

The developed course has received a high appreciation from students (based on on-line questionnaires prepared by European Commission). Based on a positive feedback obtained from students the next course is planning again in spring semester of 2009.

The similar course can be given now by author for both: academia and industry in any European university and company on demand.

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