

A research-driven multidisciplinary programme with industrial partnerships

Sheikh A. Akbar, Prabir K. Dutta, Bruce R. Patton & Henk Verweij

Ohio State University
Columbus, United States of America

ABSTRACT: The multidisciplinary research at the National Science Foundation (NSF) Center for Industrial Sensors and Measurements (CISM) at the Ohio State University (OSU), Columbus, USA, has led to a teamwork and industry-oriented curriculum development funded by the NSF-Combined Research-Curriculum Development. Under this programme, a three-course sequence in sensor materials, including instructional laboratories with industrial experience, has been developed and taught. These courses readily integrate advances in sensors, nano-materials and ceramic MEMS with direct involvement of graduate students carrying out research in CISM. Students are taking these courses and applying them towards technical electives as required by their degree programmes. These courses have also been integrated into the electronic materials track of the undergraduate degree programme in the Department of Materials Science and Engineering. This programme is now being expanded and integrated with the curriculum and training component of the NSF-IGERT programme on molecular engineering of micro-devices, which was just awarded to the OSU. Future plans include the development of a unique minor/certificate degree option at the BS level and a specialisation option at the PhD level.

INTRODUCTION

In cutting-edge research, there is a growing trend for multifaceted partnerships that involve academia, government, national laboratories and industries; however, such partnerships in education have been slower to emerge. With changing societal needs and demands, there is a need to integrate the latest research developments into the student curriculum more rapidly and to train students in a collaborative environment with involvement from industries. This will help students appreciate the impact of their education on society and will also help develop those skills considered useful for their future careers. Indeed, multifaceted partnerships provide unique opportunities to enrich the educational experiences of students that are yet to be fully exploited.

A National Science Foundation (NSF)-Combined Research-Curriculum Development (CRCD) programme has just been completed at the Ohio State University (OSU), Columbus, USA, entitled *Novel Sensors R&D Leading to Curriculum Development*. The curriculum designed under this programme takes advantage of the multifaceted partnership that exists in the NSF Center for Industrial Sensors and Measurements (CISM). CISM's organisational structure provides a framework for interaction among scientists, engineers, students and business leaders. It also provides an infrastructure that offers unique opportunities to enrich the educational experiences of students. A three-course sequence in sensor materials, which includes instructional laboratories with industrial experience, has been developed and taught at the OSU [1-4]. Further enhancing the NSF-CRCD programme, an interdisciplinary undergraduate honours course in *Sensor Materials* was also developed with funding from OSU Honors House [5].

These courses readily integrate latest research results in sensors [6-8]. The courses are team-taught by faculty members from a wide range of disciplines in engineering (such as materials science and engineering, electrical engineering, chemical engineering and mechanical engineering) and the physical sciences (chemistry, physics and computer science). Furthermore, guest lecturers, including those from industries, are brought in to cover topics where their expertise is well known. A unique aspect of this CRCD programme is that those graduate students carrying out the research are directly involved in the development and teaching of these courses.

Both undergraduate and graduate students undertake these courses and apply them towards technical electives as required by their individual degree programmes. These courses have also been integrated into the *Electronic Materials* track of the undergraduate degree programme within the Department of Materials Science and Engineering.

Future plans include the development of two new courses under an NSF-Integrative Graduate Education Research Training (IGERT) programme, which started in 2003. The key elements of the IGERT programme include the following:

- The development of new courses and curriculum;
- Dedicated research at two or more research centres;
- Industry/national laboratory internships;
- Travel to national and international meetings;
- Tours and visits to research laboratories in the USA and abroad;
- A Web-based dissemination plan.

One of the IGERT courses will be a seminar course that covers non-technical topics, such as business principles, management skills, ethics and globalisation. These five courses (3 CRCD and 2 IGERT), combined with additional technical elective courses from participating departments, will allow participating students to receive a one-of-a-kind minor/certificate degree at the BS level and a specialisation option at the PhD level.

COURSE DEVELOPMENT: EXISTING CRCD COURSES

Sensor Materials: Fundamentals

The first course, covering basic scientific principles of sensor materials, was taught for the first time during the spring quarter of 1999 as a 3-credit-hour course. In its first offering, the course was undertaken by 10 students for credit and five students audited the course. Undergraduate enrolment was very limited, primarily because it is difficult to fit in a new course on a short notice into their pre-determined curriculum. Because of early announcements, in its recent offering (autumn 2002), undergraduate enrolment was 80%. Students were given a grade based on the following:

- Three take-home tests focused on in-class lectures;
- Submission and presentation of a term paper;
- Completion of a computer simulation model of an oxide-based gas sensor.

Students were given three take-home assignments that were based on the lecture materials. These assignments were grouped under three major themes, namely:

- Synthesis and fabrication;
- Bulk and surface characterisation;
- Modelling and simulation.

Students submitted their answers electronically. A multidisciplinary team of faculty, who also graded students' answers to their questions, set the questions. Two faculty members graded each question and an average grade was assigned. The questions were open-ended and in an essay format so that students could choose from a pool of possible approaches and show their depth of understanding. The take-home assignments have been archived in the CISM repository and can be accessed as reference materials.

Each student wrote a comprehensive review paper on a selected topic. Papers were limited to 20 pages with major emphasis on the status of the current literature leading to the identification of outstanding challenges and future trends in the chosen topic. Each paper was graded by two faculty members and significant weight was given to the depth and level of critical discussion. Each student gave a *PowerPoint* presentation, which was followed by questions from the audience. The quality of the presentation was judged by multiple faculty members and a peer group of students in the class. Students submitted the term papers electronically, which have been archived in the CISM repository and can be accessed as reference materials.

Modelling and simulation play an important role in modern technological advancements, thus forming a key module of this curriculum. In this course, examples were drawn from the work of CISM in the modelling of TiO_2-based gas sensors [9][10]. Junctions between grains of n-type TiO_2 act as back-to-back Schottky barriers. Macroscopic conduction takes place by a percolative breakdown of the least resistive inter-grain barriers to form a conducting path through the granular ceramic. This example provides an opportunity for the student to simulate the electrical response of a granular ceramic based on realistic models of the electrical conduction.

In real applications, sensors will often be used in the form of an array with a gradation of properties that can provide a systematic identification of selected parameters, such as gas composition or combustion conditions. In order to extract information from a sensor array, software algorithms are needed to identify distinct features in the multiplicity of sensor data.

As a first approach, a simple neural network was trained, using gaussian basis functions, to interpolate the sensor response based on relatively sparse gas composition data. This exercise illustrated that neural nets do not extrapolate well outside of the data set they are trained on. Using the modelling of sensing mechanisms, an alternative knowledge-based kernel regression approach has been developed based on Support Vector Machine (SVM) theory. Further research will enable the prediction of gas concentrations from small arrays of sensors, which have independent responses to the different components of the gas stream.

Sensor Applications and Manufacturing

The second course covers sensor applications and fabrication/manufacturing-related issues, including micro-machining and miniaturisation. Lectures in the application area range from chemical sensors to bio-, rf- and optical-MEMS. The manufacturing area includes topics such as thick and thin films, micro- and nano-machining, replication techniques, and soft lithography.

This course also has a laboratory demonstration component. For the demonstration part, students have access to CISM laboratory facilities that include thick film fabrication by screen printing and spin coating, wide range of electrical (DC and AC) measurement equipment, a complete sensor measurement and testing facility with the capability for controlled gas flow and mixing systems, computer-controlled data acquisition and analyses with specially written software, and a GC-MS for gas-solid reaction.

It is envisaged that future offerings will utilise a thin-film and manufacturing facility that is currently being set up. Among other equipment, this facility includes a multi-cathode DC/rf magnetron sputtering unit (Discovery 18 by Denton Vacuum), bench-top sputtering unit for electrode preparation, photo-electrochemical etching set-up for preparation of nano-porous ceramic for sensing and catalysis, surface profilometer for roughness and morphology, and a bench-top tape casting unit for planar sensors and substrates.

Group Projects with Industry

The course involving group projects with industry is still evolving. The plan in these group projects is for students to target specific industries, identify a sensor need, develop a prototype and perform field-tests. Each project will be a team effort that involves multiple students working in close collaboration with a faculty adviser and an industry co-adviser. Each team will develop a sensor prototype including packaging and integration of electronics, which will then be tested in a real application in cooperation with the industry co-adviser.

Teams would be selected to ensure that students from different disciplines interact and learn from each other. Such a team approach is extremely valuable in order to make up for any deficiencies in a student's background required to take this course. Each team will submit a written report and make an oral presentation.

These types of projects help students understand the impact of their education on society and also help develop skills that will be useful for their future careers. These group projects integrate efforts already being carried out in CISM research as part of probe design and field-tests. CISM students have designed probes for CO, CO_2 and NO_x sensors and tested them in the Engine Emission and Diagnostics Laboratory at OSU [12-14].

The existing Industrial Advisory Board is utilised to identify suitable projects. It is expected that future offerings will include industry internships, where students will spend an extended period at selected industrial sites performing field tests.

COURSE DEVELOPMENT: NEW IGERT COURSES

Introduction to Molecular Engineering of Micro-devices

It should be noted that *Introduction to Molecular Engineering of Micro-devices* is the first course being developed under the NSF-IGERT programme and will be offered for the first time in spring 2003. This course presents an overview of the topical theme of the IGERT initiative and provides the needed background to bind all of the fellows in the programme as a team. The course will be team-taught by a multidisciplinary group of experts. Because of the diversified background of the fellows, the course will be graded based on group assignments with an emphasis on teamwork and communication.

This course will be composed of two parts, namely:

- Lectures covering basic scientific and technological principles of MEMD.
- Case study analysis based on a selected paper/patent.

The case study analysis will be a group assignment that leads to the preparation of a written report and an in-class presentation. The purpose of the group effort is to ensure that students from different disciplines interact and learn from each other. Such interaction would be extremely valuable in order to make up for any deficiencies in background required to take this course. In addition to in-class lectures, laboratory demonstrations, computer simulations and modelling demonstrations will be featured.

Seminar Course

The second IGERT course will be a seminar style course to be developed in close collaboration with OSU business and law colleagues. This course will cover non-technical topics, such as entrepreneurship, business principles, management skills, ethics, globalisation, patents and commercialisation. The plan is to teach this course for the first time in autumn 2003. This course will be required by all students who seek a degree option, as described in the following section.

DEGREE PROGRAMME

Students at the baccalaureate level will have the opportunity to get a minor or certificate degree in *Sensors and Measurements* on top of their primary degree. This will be achieved by going through a selected group of CRCD-IGERT courses, along with additional selected technical elective courses (existing) from participating departments, as well as the non-technical seminar course. Students at the PhD level will be able to select a specialisation option in one of the three following areas:

- Materials and manufacturing;
- Transportation and environment;
- Biomedicine.

This will be achieved by taking the two IGERT courses, along with additional selected technical courses in the area of specialisation from the participating departments.

EVALUATION AND DISSEMINATION

Assessment Plans

An external committee consisting of representatives from academia, national laboratories and industries will review the curriculum. A statistical survey carried out by specialists (ie consultants for educational methodologies and pedagogy) will track students in the programme. Students will be asked to complete a questionnaire that will be aimed at determining the success of the programme in preparing students for their careers. Based on OSU earlier offerings, it was learned what students liked and disliked, as well as what specific recommendations they had made.

It was found that students liked the following:

- Topics taught by experts, including those from industry;
- Overview talks with summary charts;
- Open-ended assignments focused around a given theme;
- Group laboratory projects and related experience;
- Computer simulation and modelling.

However, it was found that students did not like the following aspects:

- Not realising how they would be graded by multiple faculty;
- Coverage of a wide range of topics and a lack of integration.

Students have made the following suggestions:

- More group assignments to encourage collaboration;
- More guest speakers from industry;
- Industrial involvement in probe design and testing.

These comments will be taken into account in future course offerings. So as to minimise the impact of differences in grading standards, at least two faculty members will be involved in grading the same assignment. The laboratory component will involve teamwork and hands-on experience. In future offerings, some of the take-home assignments will be constructed as group projects so that students can bring their disciplinary perspectives in formulating the solution.

Also, industry members will be more efficiently involved, both for in-class lectures, as well as laboratory experiments. In particular, their expertise will be utilised for probe design and testing in real-life applications. Moreover, a Web-based course evaluation will be developed in the future to provide feedback and evaluation of those approaches and materials used in the course.

Dissemination Plans

The results of this curriculum development effort are being disseminated through the presentation and publication of papers that describe the curriculum, together with descriptions of sample capstone design projects. Papers are being presented at the Frontiers in Education Conference, and at other professional society meetings and symposia. For example, CISM faculty have presented the curriculum plans at the following:

- The International Conference on Engineering Education (ICEE-98, 99, 00 and 01) [1-3][5];
- Education symposia of professional societies, such as The American Ceramic Society (ACerS), American Society for Engineering Education (ASEE) [4], and the Minerals, Metals and Materials Society (TMS).

Future Plans

Future plans include an outreach programme aimed at undergraduates and graduates from other schools. It is planned to reach these students via a two-week summer workshop that is aimed at the faculty of these institutions. Selected modules from the five-course series will be established as an OSU course and the goal is to make these transferable so that the faculty can incorporate aspects of these modules in their own courses at their parent institutions.

It is envisaged that faculty will be provided with both experimental demonstrations, as well as the analysis software that will be developed. In addition, a set of modular courses will also be developed for OSU industrial colleagues that will have a greater focus on device fabrication and data analysis.

These modules will also be made available through the Internet, videotapes and animation CDs. Moreover, various professional societies will help disseminate this curriculum nationally through their *Education Network* programme. There will also be a strong international outreach effort under the IGERT programme.

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