HANDS-ON IN SIGNAL PROCESSING EDUCATION AT TECHNISCHE UNIVERSITÄT DARMSTADT

Tim Schäck, Michael Muma and Abdelhak M. Zoubir

Signal Processing Group
Technische Universität Darmstadt
Merckstr. 25, 64283 Darmstadt, Germany
Email: {schaeck, muma, zoubir}@spg.tu-darmstadt.de

ABSTRACT

This paper is meant to share our experience on signal processing hands-on opportunities within the formal engineering education at Technische Universität Darmstadt. It is our strong belief that undergraduate students should be offered hands-on opportunities from the very beginning of their studies until their graduation. We describe our projects, lectures and seminars that we provide undergraduate students to gain hands-on experience inside signal processing along the time line of the curriculum. We further describe the variety of laboratories that we offer to expose students to state-of-the-art research and advanced equipment. Finally, we conclude by illustrating how we use competitions to motivate and challenge students with real-world problems.

Index Terms— education, design projects, hands-on, interdisciplinarity, signal processing

1. INTRODUCTION

The integration of hands-on inside signal processing has a long-standing tradition, e.g. [1–9]. In the current era of highly complex engineering problems, it is more and more important to not only teach the required theoretical background but to also provide opportunities to develop practical "know-how" and prepare students to meet the growing demands from the engineering workforce. At Technische Universität (TU) Darmstadt, we aim at inspiring some of our colleagues who are responsible for the education of the future signal processing researchers and practitioners with this article.

Along the time line of the curriculum, which is shown in Fig. 1 and summarizes our hands-on opportunities in an ordered structure, we describe the format of projects, lectures and seminars that we offer students to gain hands-on experience. Furthermore, we briefly present the variety of laboratories of our institute. In the last Section, we illustrate how we use competitions to motivate, challenge and stimulate the collaboration between graduate and undergraduate students.

2. SIGNAL PROCESSING WITHIN THE CURRICULUM

Traditionally, the German format of undergraduate education in electrical engineering and information technology (etit) used to be the diploma degree with a standard duration of study of five years. Since 2007, a more internationally acknowledged system has been installed due to the changes relating to the Bologna Declaration.

Today, TU Darmstadt offers a three-year Bachelor's, followed by a two-year Master's degree in etit. In this Section, we explain how hands-on signal processing projects are integrated into the curriculum of etit.

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2.1. Year 1 of the Curriculum

It is our philosophy at TU Darmstadt that undergraduate students should be offered hands-on opportunities right from the start of theirs studies until their graduation. At the beginning, Freshmen are highly motivated and very curious. According to our experience, this motivation, coupled with common sense and creativity, is able to compensate the lack of fundamental theoretical knowledge in engineering. Considering all of this, the Department of Electrical Engineering and Information Technology created an introductory project for Freshmen in 2007.

2.1.1. Engineering Introductory Project

The Engineering Introductory Project consists of interdisciplinary groups of approximately ten students who work together to find a technical solution to a complex, real-world, contemporary and socially relevant problem. The duration of the project is one week and it takes place as early as 1-2 months after the starting-point of the studies in the first semester. As the students are overloaded with fundamental coursework in the early phase, the project is a welcome contrast. About 500 students participate in the project.

The Engineering Introductory Project does not focus on technical details but is designed to give a first insight into the work life of an engineer in an interdisciplinary environment. It is a good opportunity to get to know other classmates and make new friends for the remaining studies. Also, it brings students in contact with Research Associates (RAs), who supervise the groups. In Germany, RAs assist professors with teaching and research projects while pursuing a doctoral degree (Dr.-Ing.). However, RAs usually do not have to attend classes or earn credit points themselves.

Only at the start of the project, the topic of the Engineering Introductory Project is announced. Each team develops an innovative solution within one week. At the end of the week, the teams formally present their final results to a jury of professors and RAs. The topics of the projects can vary from developing a power supply-package for outdoor holidays (2008) to contributing to future life (2013).

Two RAs serve as advisers for each group: a "soft skills adviser" from the Department of Humanities assists the team in reflecting their teamwork and helps to create a pleasing group dynamic, and a "technical adviser" from the Department of Electrical Engineering and Information Technology who advises the group concerning technical aspects and engineering tools. In order to generate and evaluate possible solutions and to discover potential pitfalls throughout the project, the technical and soft skills advisers simulate the Engineering Introductory Project task some weeks before within a period of three days. The quality of the design project is improved by their experience which flows back into the project description.

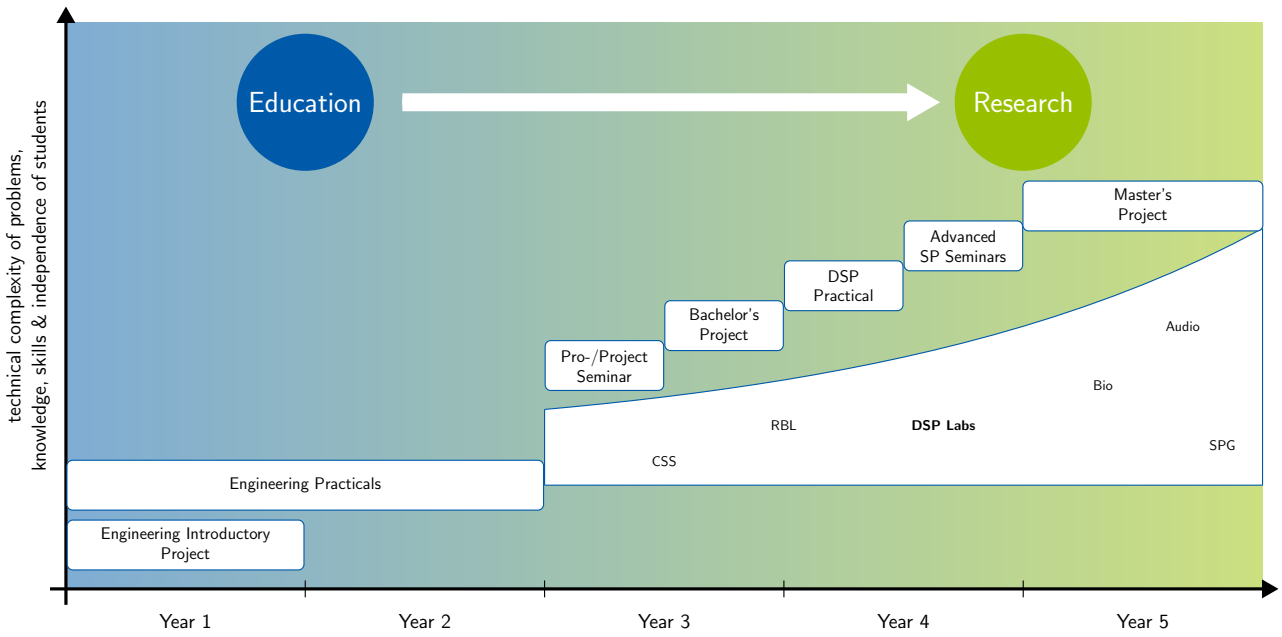

Fig. 1. Overview of the hands-on opportunities in signal processing within the curriculum of the major "Electrical Engineering and Information Technology (etit)" at TU Darmstadt. Among the Digital Signal Processing (DSP) labs are the Bioinspired Communication Systems (Bio) Lab, the Receive Beamforming Lab (RBL), the Advanced Real-Time Audio Processing (Audio) Lab, the Communication and Sensor Systems (CSS) Lab or the Signal Processing Group (SPG) Lab.

2.2. Year 2 of the Curriculum

Before undergraduate students in etit can be exposed to real-world problems in signal processing, they have to study the basics of signal processing. In the second year of their studies, our students learn the basic concepts of signal processing within the courses *Deterministic Signals and Systems* and *Fundamentals of Signal Processing*.

2.2.1. Fundamentals of Signal Processing Unit

In *Deterministic Signals and Systems*, undergraduate students learn the principles of deterministic signals and system theory. The course starts with Fourier series and the Fourier transform, treats linear time-invariant systems and convolution, and gives an overview of other signal transformations, such as the z-transform, the Laplace transform and the discrete-time Fourier transform. Students apply these transformations to solve tasks related to physical problems that can be modeled by linear differential equations.

The unit *Fundamentals of Signal Processing* subsequently covers basic concepts in signal processing, such as probability theory, random variables, stochastic processes, random signals and linear time-invariant systems, optimal linear systems, such as the matched filter and the Wiener filter, and the method of least-squares. To help the students grasp the basic ideas in an intuitive fashion, practical experiments with real-world data are shown in the lecture. The aim of this unit is to serve as an introductory course for more advanced lectures in digital signal processing, communications, adaptive filtering and control theory.

As it is common for many other fundamental courses in etit at TU Darmstadt, the lectures are complemented by biweekly tutorials, which are held by selected Undergraduate Teaching Assistants (UTAs) of higher semesters. One aspect of this idea is that signal processing can be effectively taught by senior students who have already very successfully passed the unit and know about good learning strategies and pitfalls. The UTAs who run the tutorials strengthen their knowledge in signal processing, develop their soft skills in presenting, explaining and leading, and integrate better into our research group. As a result, they usually conduct their Bachelor's or Master's thesis project with us and participate in other research projects or competitions.

2.3. Year 3 of the Curriculum

In the last year of the Bachelor's, we offer a variety of hands-on opportunities ranging from practical signal processing experiments in laboratories, such as the Communication and Sensor Systems (CSS) Lab, to small scale research projects (Proseminar/Project Seminar), which serve as a preparation for larger undergraduate research projects like the Bachelor's thesis project.

2.3.1. Communication and Sensor Systems Laboratory

The Communications and Sensor Systems (CSS) Lab consists of eight fundamental hands-on experiments from the field of communication engineering and signal processing: multiple input multiple output (MIMO) communication, software defined radio, localization of acoustical sources, parasitic effects in passive radio-frequency (RF) devices, polarization of light, digital modulation, RF field-effect transistor (FET) amplifier, and fields and impedance of antennas. The students are guided to acquaint themselves with each topic. For each experiment, they write a report about their results and answer comprehension questions. This laboratory is the first opportunity for students in the third year to experience hands-on with electronic equipment where they can apply the freshly learned fundamentals of signal processing. This lab also fosters the ability to work in teams.

2.3.2. Bachelor's Thesis Project

Bachelor's thesis project concludes the third year and usually builds upon the Proseminar and Project Seminar. The Bachelor's thesis project is designed to last three months. Typically, the length of the Bachelor thesis is around 40–80 pages. Each year, about 100 students in etit finish their Bachelor thesis. The students have to give a

20-minute presentation and defend their work in front of an audience at the end of their Bachelor's thesis project. It offers the possibility for students to be creative and to develop new ideas and algorithms. Students can either explore new ways of solving a specific problem, compare different methods by assessing their performance using simulated or real-world data, or improve an existing approach by extending or enhancing particular aspects. Commonly, the topic of the Bachelor's thesis project is chosen by the RAs and fits into their research areas. Sometimes, outstanding Bachelor's thesis projects lead to publications [10–12] and visits to conferences such as the IEEE Workshop on Statistical Signal Processing (SSP), EUSIPCO, or ICASSP.

2.4. Year 4 and 5 of the Curriculum

During the Master's program, which forms the final two-year stage of the undergraduate education at TU Darmstadt, students are offered advanced engineering projects and activities to deepen their knowledge in signal processing and to gain hands-on experience on real data.

2.4.1. Digital Signal Processing Practical

In their fourth year, students can attend the *Digital Signal Processing (DSP) Practical*, either in parallel to or after the course *Digital Signal Processing*. It offers the chance to further familiarize themselves with signal processing programming (e.g., in Matlab) and put theory into practice. Students participating in this practical are able to apply the concepts from the lectures. The DSP Practical mainly covers the design of finite impulse response (FIR) and infinite impulse response (IIR) filters as well as parametric and non-parametric spectrum estimation. Real-world signals, such as speech and audio signals, touch-tone telephone dialing signals, temperature recordings, or biomedical measurements are either provided to or recorded by the students. UTAs help supervising the undergraduate students during the experiments. The experiments are conducted in the SPG Lab, which is described in Section 3.1.

The *DSP Practical* is composed of eight practicals and two real-data acquisition sessions. About ten groups of two to three students work together to solve signal processing tasks. As an introductory part for every experiment, students receive handouts with the underlying theory and some preparatory questions. The students' understanding of the theory is checked by the supervisor at the beginning of each experiment. In this way, we ensure the students' adequate preparation for the practicals. Furthermore, for every experiment, each group writes a report, in which they wrap up their results, answer given questions, and include plots and code from the experiment. At the end of the semester, a final written exam is held which focuses on understanding of the concepts rather than mathematical derivations.

2.4.2. Advanced Seminars in Signal Processing

In their fourth and fifth year, signal processing students at TU Darmstadt have acquired sufficient fundamental knowledge and are ready to tackle some more challenging and realistic problems. By this time, they are also used to reading and reproducing results from papers. To prepare for their Master's thesis project, to provide the opportunity to get to know the RAs, and to practice working in teams, the SPG offers an advanced seminar, in which Master's students tackle small scale real-world problems. The seminar is simply called *Advanced Topics in Statistical Signal Processing* and it is aimed at students with an interest in signal processing and a desire to extend their knowledge of signal processing in preparation for future project work, e.g., their Master's thesis project and their working careers. The seminar consists of a short series of lectures (4-5), followed by student group projects (6-8 weeks), a presentation of the achieved results, and a final exam. Usually, up to 20 students participate in the seminars. The topics of the lectures and also the student projects differ every year. The RAs are free to propose topics for the student projects and the students make their choice based on their own interest. In this way, both the students and their supervisors are highly motivated. Students often use the SPG Lab to investigate topics such as direction-of-arrival estimation, localization of sound sources in impulsive noise environments or biomedical signal processing, e.g. based on electrocardiogram (ECG) or photoplethysmogram (PPG) measurements. In many cases, students become creative in the experiments and go beyond simple application of the learned concepts.

2.4.3. Final Year Master's Thesis Project

The four-semester Master's program in etit consists of compulsory core courses, compulsory elective courses, and elective courses as well as the Master's thesis project. In their Master's thesis project, the students work independently for a duration of six months on a scientific project under the supervision of one of the RAs. The research topics are larger and more complex compared to the Bachelor's thesis project.

The Master's thesis project often offers the possibility to conduct research on more advanced real-world data. From our experience, the best results are obtained when the students are involved in collecting their own data. In this way, they acquire hands-on contextual information and can better understand the data, e.g. in terms of the signal quality, the measurement principle or the assumptions on the noise distributions. Further, when the Master's thesis project solves a real-world problem, the students take more care that the developed algorithms are designed in accordance with practical requirements. The latter include, e.g., communicational load between sensors, computational efficiency of the algorithm, real-time requirements, or memory restrictions. In our experience, the students enjoy incorporating such realistic requirements into their algorithm design.

3. LABORATORIES

From the starting-point until graduation, the signal processing laboratories at TU Darmstadt are the core to our hands-on education. In this Section, we presents our diverse signal processing laboratories and the opportunities they offer for signal processing students.

3.1. Signal Processing Group (SPG) Lab

In our group, we offer hands-on experience to the students in the Signal Processing Group (SPG) Lab. It consists of a basic audio signal processing lab, a biomedical sensor lab, a synthetic aperture sonar lab, and a radar lab, which is exemplarily shown in Fig. 2 during a measurement to recognize the human gait in cane-assisted walks. It is mainly funded by the so-called "Resources for quality assurance of study and teaching" (QSL), a fund for enhancing hands-on in teaching. In the biomedical sensor lab, a variety of sensors offer the opportunity to acquire own measurements, such as a respiration belt, ECG, PPG, blood pressure (BP), etc. The data is recorded using devices from ADInstruments which are originally designed for research and teaching at universities [13].

3.2. Advanced Real-Time Audio Processing Lab

For the development of DSP algorithms, which show good and robust performance in real product applications, real-time tests with typical signals in realistic environments are essential. Those real-time tests cover a variety of natural setups which cannot be covered by data simulations. The research group Adaptive Systems for Speech and Audio Signal Processing of Prof. Puder provides such a system for the development of audio processing algorithms in student projects. The core component is a real-time DSP system, Speedgoat [14], with 12 analogue audio input and 8 output signals. The signals are processed with low latency (< 1 msec). Algorithms

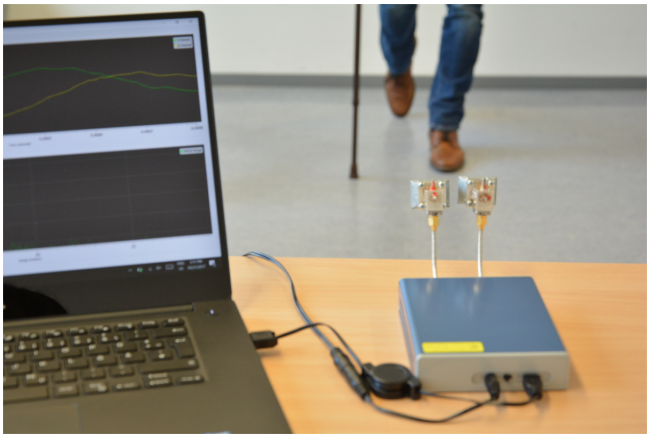

Fig. 2. A measurement to recognize the human gait in cane-assisted walks taken in our radar lab.

can be implemented in high-level programming languages such as Matlab/Simulink. To this end, a compiler converts the Simulink code to C-code, which can be run natively on the Speedgoat system.

A research focus of the Audio Signal Processing Group of Prof. Puder is the development of algorithms for hearing devices such as hearing aids or hearing aid glasses with a focus on feedback cancellation and beamforming. Such hearing systems need to be evaluated under realistic conditions, i.e., worn on a head not in a free-field. We use the KEMAR [15] as a well established head model. This allows to model the head with respect to head shading as well as to model the ear channel, which is necessary for realistic feedback tests of hearing aid devices.

3.3. Bioinspired Communication Systems Lab

The Bioinspired Communication Systems Lab of Prof. Koeppl conducts research in statistical signal processing and machine learning in the context of biomolecular systems. Due to the availability of wet-lab facilities in the group, students can generate their own data by performing single-cell experiments involving fluorescence microscopy and microfluidics. The microfluidic chips used for student projects are further optimized and fabricated in house. The hands-on work also involves the processing of raw imaging data to obtain accurate segmentation and temporal tracking of single cells.

3.4. Receive Beamforming Lab

The Communication Systems Group of Prof. Pesavento offers a student experiment in the field of multi-antenna receive beamforming. The experiment is based on the WARP v3 Kit by Mango Communications [16] which includes an easily accessible Matlab interface. The main idea of the experiment is to give students insight into the application of receive beamforming as part of a complete transmitter-receiver chain: starting from the antennas, which were designed at TU Darmstadt specifically for the experiment, and ending with digital baseband signal processing algorithms implemented in Matlab. A main challenge in the design of the experiment consists of finding the best trade-off between performance and complexity on the one hand, and comprehensibility of the exercise on the other.

The goal of the experiment is to provide user data separation by means of receive beamforming. For ease of implementation, a simple Matlab interface is provided which students can use to perform all the required signal processing. As a result, students can directly focus on the beamforming implementation.

4. COMPETITIONS

From our experience, students who took part in competitions show not only higher technical understanding but also higher motivation and enthusiasm. They are inspired by their hands-on experience and their voluntary and ungraded achievements, which can also lead to better overall performance in their studies. One important aspect is again teamwork. If the team works harmoniously and everyone enjoys their time, creativity skyrockets. In case of a successful outcome of the competition, students gain additional benefits from having the possibility to visit a conference, receive a prize, or prestige.

Together with the German Association for Electrical, Electronic & Information Technologies (VDE), Rohde & Schwarz organizes an international case study competition for undergraduate students [17] in the field of mobile communications.

In 2012, the student team "Shannon's Hounds" of the SPG took part in the case study competition whose theme was "Engineer the future! The future of mobile communications is on you". In the competition, in which 220 students from Germany and Singapore participated, students had to solve complex tasks concerning the ISO/OSI-layers of the LTE cellular network. At the finals in Munich, modern measurement equipment provided by Rohde & Schwarz was used in order to find solutions. "Shannons's Hounds" performed outstandingly well and won the competition against ten teams from Germany and Singapore. Each team member received an Apple iPad and EUR 2,000 prize money for the university. As it was the wish of the team, the prize money was spent on hands-on experiments for teaching purposes. Two out of the five members of the team are now RAs with the SPG and one is with the Communications Engineering Group.

The IEEE Signal Processing Cup was initiated in 2013 by the IEEE Signal Processing Society to increase students' interest in signal processing and to raise their awareness of its applications in real life [18]. Undergraduate students are provided with an opportunity to form teams and work together to solve a challenging and interesting real-world problem using signal processing techniques and methods. In the first competition 2014, approximately 100 undergraduate students from all over the world took part in 25 different teams.

In 2015, the SPG decided to take part in the second edition of this prestigious competition with its student team "Signal Processing Crew Darmstadt". The task of the competition was to estimate the heart rate using photoplethysmographic (PPG) signals recorded from subjects' wrists during physical exercise. See [19] for more information on the competition. The RAs Michael Muma and Tim Schäck recruited seven students with interest and motivation in signal processing in August 2014. The SPG team won in a tough final competition at ICASSP 2015 in Brisbane, Australia, against brilliant competitors from Bangladesh and South Korea. The main part of our prize-winning algorithm [20] was published at EUSIPCO 2015 in Nice, France, and was co-authored by one of the undergraduate students, who also continued working on heart rate estimation in his Master's thesis project.

5. CONCLUSION

Technische Universität Darmstadt is strongly committed to engaging undergraduate students in hands-on signal processing practice. Exposure to practical experiments is integrated into all phases of the curriculum and a variety of laboratories have been created. Students are encouraged to participate in research projects, industry collaborations and student competitions that address exciting new problems. In this way, we educate, motivate and encourage a new generation of signal processing researchers and practitioners to face the challenges that only real-world applications can provide.

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