AC 2007-976: FACILITATING ENGINEERING MATHEMATICS EDUCATION BY MULTIDISCIPLINARY PROJECTS

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Facilitating Engineering Mathematics Education by Multidisciplinary Projects

Abstract

Engineering students generally do not perceive mathematics in the same way as professional mathematicians usually do. They need to have it explained to them why knowledge of mathematics is essential for their studies and their future profession. Project based learning turned out to be a particularly suitable method to demonstrate the need of mathematical methods, since there seems to be no better way of acquiring comprehension than if it arises from personal experience. The students are confronted early on in their courses with challenging problems arising in industry. These problems are usually of a multidisciplinary nature and have in common that the mathematical competencies needed for their solution are slightly beyond the students' skills. Having realized the gap in their knowledge of mathematical methods, students are eager to bridge it, thus drawing their attention towards their mathematics education. It is important to design the lectures in such a way that the students' demands are satisfied. Then their attentiveness increases immensely and often leads to interaction and feedback during formal lectures. Sometimes students even ask for additional lectures, which may become necessary to satisfy the needs of some project tasks.

The students are offered a variety of project proposals at the beginning of the semester. They can choose their project work according to their interests**.** Usually a team of three works on a project, for more comprehensive tasks a team of four students is approved. In this way generic skills required by industry are also developed. Generally, two or three groups are assigned the same task. This introduces a competitive aspect, which in turn increases the students' motivation. The outcome of some of these undergraduate projects has found application in industry or has been published in professional journals.

In this paper the idea of project based learning in engineering mathematics is exemplified on the basis of students' projects carried out in the third semester of their degree program.

Introduction

It seems that the critical issue in teaching mathematics to engineering students is to find the right balance between practical applications of mathematical methods and in-depth understanding [1]. Project based learning has proved to be a particularly suitable method to demonstrate the need of mathematics in professional engineering. Students are confronted, complementary to their regular courses, with problems that are of a multidisciplinary nature and demand a certain degree of mathematical proficiency. A particularly suitable way of doing so turned out to be the establishment of interdisciplinary project work in the early stages of the degree program.

The courses Information Systems and Programming in the second and third semester of degree program Automotive Engineering at the Joanneum University of Applied Sciences form the basis for project (and problem) based learning. In the second semester the programming language Visual Basic (VB) is introduced. It enables the students to develop graphical user interfaces (GUIs) with comparatively little effort. In the third semester ANSI C, a machine-oriented programming language that enables both the programming of microcontrollers and the implementation of fast algorithms, is taught. Additionally, the existing VB knowledge from the second semester is utilised by accessing dynamic link libraries (DLLs), programmed in C, from user friendly VB GUIs. In both semesters the students have to complete software projects as part of the requirements of both the Information Systems and Programming course, and at least one additional course within the curriculum. Generally the project is formulated within this so-called ‘complementary’ course and covers a typical problem in the field of that subject. Usually a team of three students works on a project, for some tasks a team of four is approved. One of them is designated by the team as project leader and assumes the competences and responsibilities for this position. This structure promotes the development of certain generic skills, like the ability to work in teams, to keep records and to meet deadlines. Up to three groups are assigned with the same task. In this way competition is generated, which in turn increases the students’ motivation. While in the second semester the main focus is on the acquisition of programming abilities and on soft skills, the tasks of the third semester projects focus more on the subject area of the complementary courses. Those courses typically are Engineering Mathematics, Mechanics, Strength of Materials, Machine Dynamics, Thermodynamics, Fluid Mechanics, and Measurement Engineering. Furthermore, the course in General English is involved in the third semester projects due to the designation of English as the overall project language.

It is essential for the educational concept introduced in this paper that the degree of difficulty at the start of the projects seems to be beyond the present capabilities of the students. The knowledge and skills necessary to complete the tasks successfully will be taught during the course of the semester, thus producing an increased interest on the part of the students in the subjects they are studying. In this way we can compensate for one of the weak points in the educational system, namely the lack of time for reflection on knowledge gained and the interconnection of the different disciplines taught. A further benefit is the increased acceptance of the English language within the core of the engineering education program.

The students are offered a variety of project proposals at the beginning of the semester. They can choose their project according to their interests and skills. The lecturers who propose a topic supervise and support the project groups. The projects’ demands and the work load are continuously evaluated in order to avoid overburdening the students. The projects’ schedule starting from the presentation of the proposals, the kick-off meeting and further milestones, as well as the presentation and evaluation are described elsewhere [2].

Project/Problem Based Learning in Engineering Mathematics

The curricula of the engineering degree programs at our university include engineering mathematics in the first three semesters. The lectures follow typically the contents of text books like Kreyszig’s *Advanced Engineering Mathematics* [3], with an emphasis on numerical methods in the third semester. To speak from the first author’s own experience, lectures in numerical mathematics in particular can be rather boring. The reason for this is often the students’ lack of understanding of the usefulness of the methods presented. The application of numerical algorithms normally happens for the first time years after the mathematics lectures, e.g. in the course of the graduate thesis. Software projects complementary to the lectures offer the opportunity to show the students quite plainly the value of the just learned methods and algorithms, thus increasing their attentiveness and their appreciation for the new topics.

Furthermore, projects give students the chance to look beyond the standard curriculum of engineering education. For instance, in terms of time-frequency analysis only the Fourier Transform (FT) is covered by common engineering mathematics curricula. In our curriculum, the continuous transform is introduced in the second semester, the discrete transform (DFT) as part of the numerical methods in semester three. But in many engineering problems one is interested in the frequency content of non-stationary signals and its localization in time. It has to be pointed out to the students that with FT they are still not equipped with the appropriate tools for tackling such problems. This is best done by first presenting them a problem where both temporal and spectral information of a signal are of importance. Typical problems in automotive engineering can be crack detection in bearings or gears, and vehicle acoustics. As soon as students are aware that they are lacking appropriate methods for the solution of their problem, they are eager to learn more. In this way their interest in the apparently dry and dreary numerical mathematics can be revived tremendously. In the first of the three examples specified below the students' task was the implementation of a discrete wavelet transform. The wavelet analysis is probably the most recent solution to overcome the shortcomings of the Fourier transform. This fact comprised the additional benefit that young engineering students were concerned with a field of mathematics not older than two decades.

Another important factor contributing to the acceptance and success of these projects is the usefulness and applicability of the outcome. Students are highly motivated by tasks that stem from real engineering problems arising from their field of study. The second example specified below resulted from a conjoint research project with BMW [4]. The objective of this work was the investigation of aerodynamic improvements by the application of underfloor panels. A coastdown method with minimal instrumentation effort was chosen to determine drag coefficients on the road. The students' task was the creation of the evaluation program for this method.

As third and last example a project arising from a contemporary scientific research problem is presented. The students' task was to develop a program that facilitates the data reduction and data analysis of coincidence Doppler broadening spectra of positron annihilation. The spectrum is sampled by two detectors and therefore a function of two energies, and can be displayed as a two-dimensional plot. The main problem in data reduction was to find the axis, which represents the coincident events, and to make the data along this axis available for further analysis. With this project it could be demonstrated that undergraduates can successfully be involved in up-to-date scientific problems, provided that the supervisors limit the scope to manageable pieces of work.

Example 1: Discrete Wavelet Transform

The project proposal was:

The need for a combined time-frequency representation stemmed from the inadequacy of either time domain or frequency domain analysis to fully describe the nature of non-stationary signals. A time-frequency distribution of a signal provides information about how the spectral content of the signals evolves with time, thus providing an ideal tool to dissect, analyse and interpret non-stationary signals. This is performed by mapping a one dimensional signal in the time domain into a two dimensional time-frequency representation of the signal.

Your task is to develop a C-program with VB GUI that enables the user to perform a Discrete Wavelet Transform (DWT) of discretely sampled data, which are provided as ASCII files or as output of MultiChannelScope (MCS). Existing algorithms can be utilized. Both time signal and transformed data shall be illustrated and data analysis and printout should be enabled. Your program should be developed in consideration of the necessities of the intended advancement of the existing MCS software.

A wavelet, in the sense of the DWT, is an orthogonal function which can be applied to a finite group of data. Like the Fast Fourier Transform (FFT), the DWT is a fast, linear operation that operates on a data vector whose length is an integer power of two, transforming it into a numerically different vector of the same length. Also like the FFT, the wavelet transform is invertible and orthogonal. Both transforms are convolutions and can be viewed as a rotation in function space. But contrary to the FT the wavelet transform is capable of providing the time and frequency information simultaneously, hence giving a time-frequency representation of the signal.

Whereas the basis function of the Fourier transform is a sinusoid, the wavelet basis is a set of functions which are defined by a recursive difference equation

$$\varphi(t) = \sum_{k=0}^{N} c_k \varphi(2t-k), \qquad (1)$$

where the range of the summation is determined by the specified number N of nonzero coefficients c_k. The number of nonzero coefficients is arbitrary, and will be referred to as the order of the wavelet. The value of the coefficients is, of course, not arbitrary, but is determined by requirements of orthogonality and normalization [5].

The functions which are normally used for performing transforms consist of a few sets of coefficients resulting in a function with a characteristic shape. Two of these functions should be implemented by the students in their project; the first is the Haar basis function, chosen because of its simplicity, and the second is the Daubechies-4 wavelet, chosen for its usefulness in data compression. The nonzero coefficients c_k which determine these functions are $c_0 = 1$ and $c_1 = 1$ for the Haar wavelet and $c_0 = (1+\sqrt{3})/4\sqrt{2}$, $c_1 = (3+\sqrt{3})/4\sqrt{2}$, $c_2 = (3-\sqrt{3})/4\sqrt{2}$, $c_3 = (1-\sqrt{3})/4\sqrt{2}$ for the Daubechies-4 wavelet. An appropriate way to solve for values of equation (1) is to construct a wavelet coefficient matrix and applying it hierarchically, first to the full data vector of length N, then to get values at half-integer t, quarter-integer t, and so on down to the desired dilation [6].

The program developed by the students consists of a Visual Basic part and a C DLL. The VB part was mainly used for the visualization of the input and manipulated data (see Figure 1) while the DLL-File was optimized for data transfer and the wavelet transform. Three different wavelet transforms were enabled; Haar, Daubechies-4, and Daubechies-6 basis functions were implemented.

Another feature of the program is data compression by filtering. In contrast to Fourier transform both high- and low-frequency characteristics of a signal are preserved when keeping only the high amplitude components of the transformed data. The reason for that is that the time localization of the frequencies will not be lost in DWT. The frequency bands that are not very prominent in the original signal have very low amplitudes, and that part of the DWT signal can be discarded without any major loss of information, thus allowing data reduction.

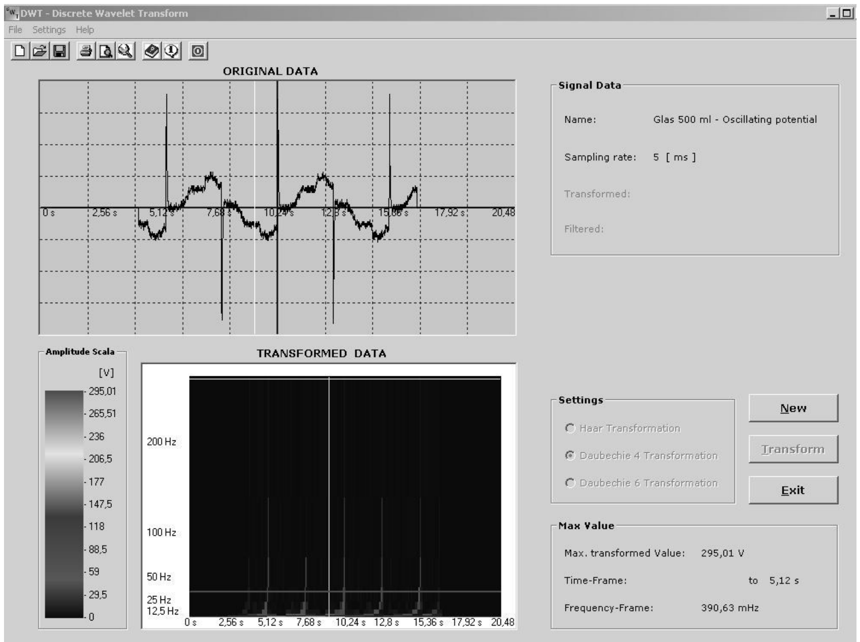

Figure 1 GUI of the DWT program designed by a project group. In the upper window the discretely sampled time series is represented, in the lower window the time-frequency representation of the wavelet transform is illustrated. MS Windows standards have been applied to the icon arrangement for comfortable and easy use.

Figure 2 shows the original signal consisting of 4096 measured data (white) and the back transform (black) which was reconstructed from the 40 wavelet components highest in magnitude. Daubechies-4 basic functions were used for the wavelet transform. The closeness of agreement obtained with less then one percent of information is amazing.

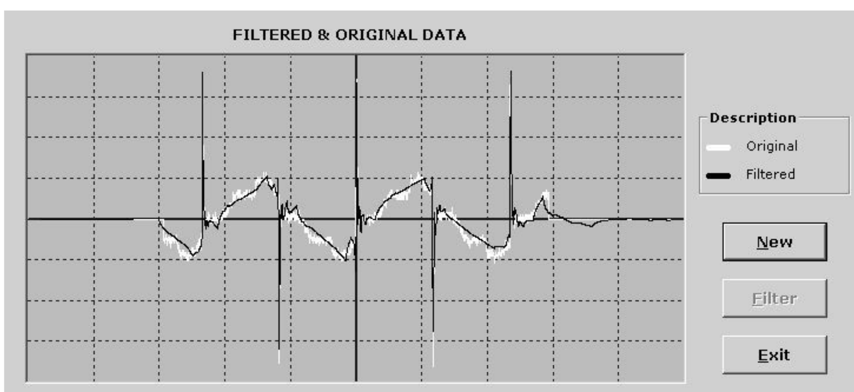

Figure 2 Illustration of the sampled time series (white) and the representation of the inverse wavelet transform (black) of the 40 wavelet components highest in magnitude out of 4096 components.

In this project the students' attention was directed towards orthogonal transforms, time-frequency analysis, filters, data compression, and visualization of data. They benefited from supplementary lectures in wavelet analysis and did their own research in a field of mathematics that is less than two decades old.

Example 2: Aerodynamic Drag

The project proposal was:

The coastdown method can be used to estimate the drag forces that act on a vehicle when operating in its natural environment. The experimental technique is remarkable in its simplicity. The vehicle is accelerated to a desired upper speed, declutched, and then allowed to decelerate under the action of the various drag forces. Primarily only the vehicle velocity has to be recorded during the coastdown, but most contemporary coastdown investigations make use of additional measurement data. In a recent approach the aerodynamic drag of different vehicle configurations is investigated by only considering the motorcar's speed data retrieved from the control area network data bus during the coastdown. The velocity data of all configurations are reduced simultaneously by constrained linear inversion of the equation of motion.

Your task is to develop a C-program with VB GUI that enables the user to calculate the drag coefficients by simultaneous constrained linear inversion of coastdown data. The quality of the thus obtained coefficients shall be examined by the comparison of the measured speed time history with the integrated equation of motion.

The determination of the aerodynamic drag is of considerable importance since it negatively influences characteristics like consumption, maximum speed and acceleration. Existing methods for the determination of aerodynamic drag include wind tunnel tests and on-road investigations such as the coastdown method. The procedure of the latter is as follows: The vehicle is accelerated to a defined upper speed and declutched. It then coasts freely until a defined end speed is reached. During this coastdown the velocity data is recorded (see Figure 3). This method is remarkable in its simplicity and thus very cost-effective.

The equation of motion for a vehicle coasting down freely in a straight horizontal line may be expressed as

$$F_{rm}\left(v(t),T\right)+c_d\,\frac{\rho\,A_f}{2}\,v(t)^2=-m\,\frac{dv(t)}{dt}\,. \tag{2}$$

The rolling and mechanical losses F_{rm} are a combination of the tire losses and losses from the drive train and the un-driven wheels; A_f represents the vehicle's frontal area, m the vehicle's mass and ρ the air density. Rolling and mechanical resistance is a non-linear function of speed and in addition temperature-dependent. For a simplified description of the rolling resistance a polynomial in $v(t)$ and only a non speed-dependent rolling resistance $F_{rm}=c_{rm}\,m\,g$, representing an average value within this speed range, are commonly used.

Introducing the new variables $a_1=c_{rm}\,m\,g$ and $a_2=c_d\,\rho\,A_f/2$ and the above specified approximations, equation (2) can be formulated as

$$a_1+a_2 v(t)^2=-m\,\dot{v}(t)\,. \tag{3}$$

Equation (3) represents a separable first order differential equation with constant coefficients, which can easily be solved. Based on its solution the drag coefficients can be determined by a least squares parameter fitting to the measured speed-time history. Another approach is to differentiate the recorded velocity data numerically in order to get the deceleration of the coasting car. In this way velocity and acceleration of the vehicle are available for each scanning instance t_k.

The discrete data sampling transforms the differential equation (3) into a set of linear equations that can be comfortably expressed in matrix notation

$$\begin{pmatrix} 1 & v(t_1)^2 \\ 1 & v(t_2)^2 \\ \vdots & \vdots \\ 1 & v(t_M)^2 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = -m \begin{pmatrix} \dot{v}(t_1) \\ \dot{v}(t_2) \\ \vdots \\ \dot{v}(t_M) \end{pmatrix} \tag{4}$$

or shorter $A\vec{a} = \vec{b}$.

If in the course of the investigations only the aerodynamics of a vehicle is altered and the rolling resistance remains essentially unaffected during each run, the coefficient a_1 should remain unchanged for all aerodynamic configurations. This requirement can be implemented into the least squares procedure by solving it for all j coastdown data sets in conjunction with simultaneous consideration of appropriate constraining condition $q(a_{1,j})$ so that not only $(A\vec{a} - \vec{b})^2$ is minimized but

$$(A\vec{a} - \vec{b})^2 + \lambda q(a_{1,j}) = \min., \tag{5}$$

where λ is a Lagrangian multiplier. In this way the coefficients a_2 of the different vehicle configurations and thus their aerodynamic drag coefficients c_d can be determined [7].

In Figure 3 the velocity-time histories of the coastdowns of a vehicle with three different aerodynamic configurations is illustrated. The students' task was the evaluation of the aerodynamic drag coefficients of the different vehicle configurations from those time series.

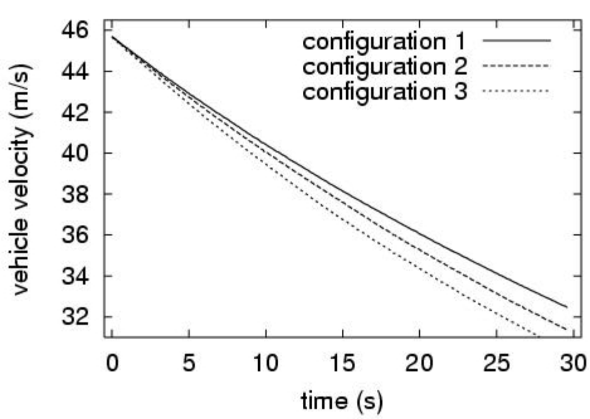

Figure 3 Vehicle velocities during the coastdowns. The recording was triggered at a start speed of 160 km/h and stopped after the same length of time. Three different aerodynamic configurations of the same vehicle were investigated.

In Figure 4 the results of equation (5) for five different aerodynamic vehicle configurations are illustrated as a function of λ. The second components of the vectors $\vec{a}$ are therein converted into the physical relevant drag coefficient c_d. Due to the constrained c_{rm} the aerodynamic drag coefficients are somewhat dispersing with increasing λ (see Figure 5). The drag coefficients of two different configurations coincide apparently with $\lambda \sim 0$ but separate considerably with increasing λ. Additionally, another pair of coefficients changes its arrangement. The choice of an appropriate λ depends on the magnitude of the entries of the matrix A.

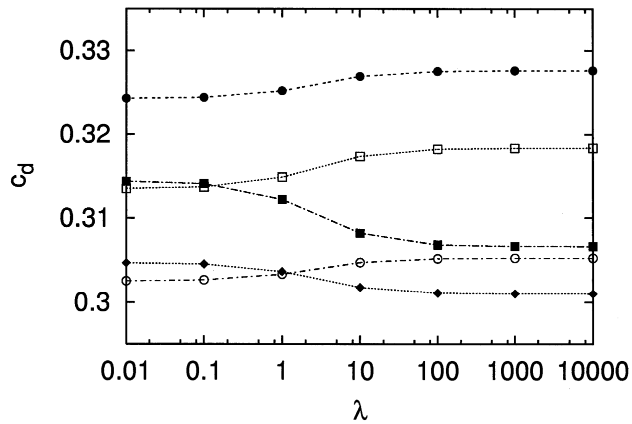

Figure 4 Aerodynamic drag coefficients c_d of five different vehicle configurations as a function of λ

In order to verify the accuracy of the above described method of analysis the differential equation (3) is then solved in the program by employing the drag coefficients obtained from equation (5) for $\lambda \geq 10^5$. As initial values for the solution of the first order ordinary differential equation the entry speeds of the coastdowns are taken. The deviation from the experimentally determined vehicle velocities is a measure of the quality of the analysis method.

The program was provided with a user-friendly GUI, including a multiple document interface for optimal comparability, and data transfer to MS Excel was established. All the necessary calculations are performed automatically. It is available free of charge and can be downloaded from our department's homepage [8].

In this project the students had to deal with constrained linear inversion problems, numerical differentiation, numerical solutions of differential equations and the effect of measurement inaccuracy on the outcome of complex algorithms. It was highly motivating for the young students that they could cope with a task assigned by industry (BMW) in which they were entrusted with the solution of an up-to-date problem in vehicle aerodynamics.

Example 3: Positron Annihilation Spectroscopy Data

The project proposal was:

Positron annihilation spectroscopy is a sensitive probe for studying defects in solids. Recent theoretical progress renders it feasible to identify different elements from their annihilation spectra and thus offers the possibility to probe the chemical environment of defect sites acting as traps for positrons. From the experimental point of view this requires the measurement of high-momentum regions of Doppler annihilation spectra at sufficiently low background which can be achieved most efficiently in a coincidence experiment using two germanium detectors.

The strength of this technique has already been demonstrated successfully in several investigations.

Your task is to develop a C-program with VB GUI, which enables the user to cut out data along the diagonal of the 2D-spectra manually or automatically with variable width and subsequent visualization of the resulting 1D-plot. Additionally, the data thus obtained shall be normalized and saved in an ASCII file to enable further investigations.

Positron annihilation spectroscopy is nowadays well recognized as a powerful tool for microstructure investigations of condensed matter. Positrons can be obtained from β^+-decay of radioactive isotopes or from nuclear reactions. For the investigation of the electronic structure of defects in solids they are implanted into the sample and move through the medium until they reach thermal equilibrium. As the antimatter counterpart to the electron, the positron remains only a short time (10^{-10} s) in the sample before annihilating with an electron under emission of annihilation gamma rays that escape the system without any interaction. The spectrum of these gamma quanta holds information about the electronic environment around the annihilation site [9]. The principle of the method lies in the analysis of the positron annihilation line shape, which directly corresponds to the distribution of momentum of electron-positron pairs. The momentum itself is measured from the amount of the Doppler shift of the emitted photons. The high-momentum part of the Doppler-broadened spectra can be used to distinguish different elements at the annihilation site. This can be achieved by using a two-detector coincidence system, which reduces the peak to background ratio dramatically [10]. The coincident events have to be extracted from a two-dimensional spectrum that is recorded by two high-purity germanium detectors. For this purpose the students' task was the development of a computer program, which allows an automated data reduction from such Doppler-coincidence spectra, supplemented by a post-processing unit for data analysis.

Figure 5 shows a two-dimensional spectrum recorded from positron annihilation in aluminum represented by "MePASto", the computer program developed by the students within this project. For every coincident event, the energies of both gamma rays (denoted by E_0 and E_1) are registered in two detectors arranged at 180° to each other on both sides of the aluminum probe. These energies form the vertical and horizontal axes, and the count corresponding to each E_0 and E_1 combination is indicated in color, depending on their absolute values. The intense central peak centered at $E_0 = E_1 = 511$ keV corresponds to annihilation with valence electrons. The elliptical region extending diagonally with $E_0 + E_1 \sim 2m_0c^2 = 1022$ keV originates from annihilations with high momentum electrons, and this region is nearly background free. A cut along the diagonal can then be analyzed to observe variations in shape due to the contributions of core electrons. Due to different detector efficiencies the actual axis of coincidence is in general not exactly the diagonal of the two-dimensional data array.

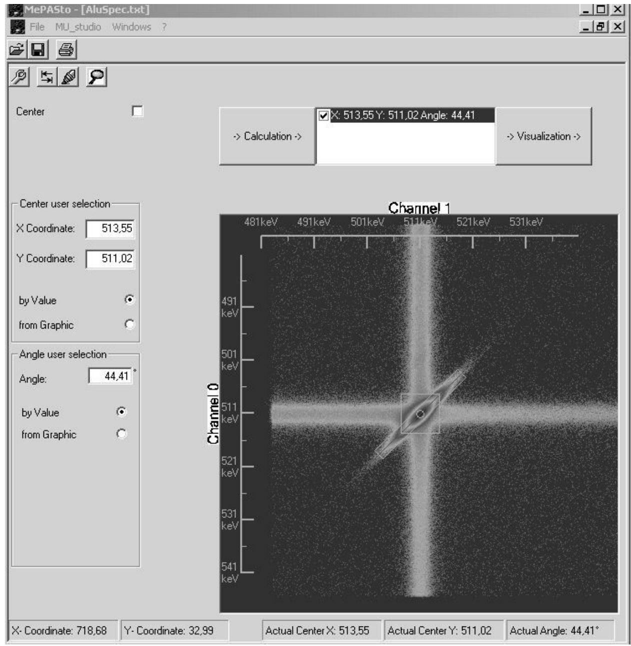

Figure 5 Positron annihilation spectrum of aluminum in MePASto's graphical user interface. The spectrum contains a total of $33 \cdot 10^6$ events.

The main task of the data reduction routine was the localization of the central peak, which represents the rest mass of the electrons, and the $E_0 + E_1 = 1022$ keV diagonal axis of the coincident events.

Polar coordinates centered at the 511 keV peak were employed for the determination of this axis. Within the angular range 40° to 50° the interpolated data entries were summed up along a straight-line within an interval of 100 pixels in steps of one hundredth of a degree. If a pixel was only touched, an interpolation algorithm took care that it got the correct weight. The angle that gave the highest sum was used as the origin for a succeeding procedure. The line with the maximum sum was then taken as a starting point for a least squares data fit. It was divided into intervals of adjustable width and then the maximum in a slice perpendicular to the line was located for each interval. The data points gained in this way were fitted to a straight line, which eventually represented the optimized cut in the 2D spectrum. The data fit could be performed optionally with keeping the 511 keV point fixed or free as a fitting parameter. Relativistic effects on the core electrons of heavy elements result in a small deviation of the coincident events from a straight line, which should lead to a small shift of the regression line, if the center of gravity is allowed to move.

The program also enables a user defined cut of the ($E_0 + E_1$)-axis by mouse clicking in the 2D spectrum, which gives an additional degree of freedom. Parameter studies showed that the human eye is an excellent analyzing instrument. Most of the visually determined cuts along the coincidence axis resulted in spectra with no significant deflection from the calculated ones.

Different interpolation algorithms were implemented in the program. By default a bilinear interpolation algorithm was in use, where only the nearest neighbor pixel entries had to be taken into account. A bicubic interpolation algorithm, which requires the specification of not only the neighboring grid points but also their derivatives [6], and an interpolation scheme, which takes the inverse distances of the neighbor pixels as weights, were additionally made available in the program.

In Figure 6 the coincidence spectrum of the aluminum measurement is shown. It corresponds to a projection onto ($E_0 - E_1$)-axis from Figure 5. The width of the sum energy window is selected to exclude vertical and horizontal bands depicted in Figure 5.

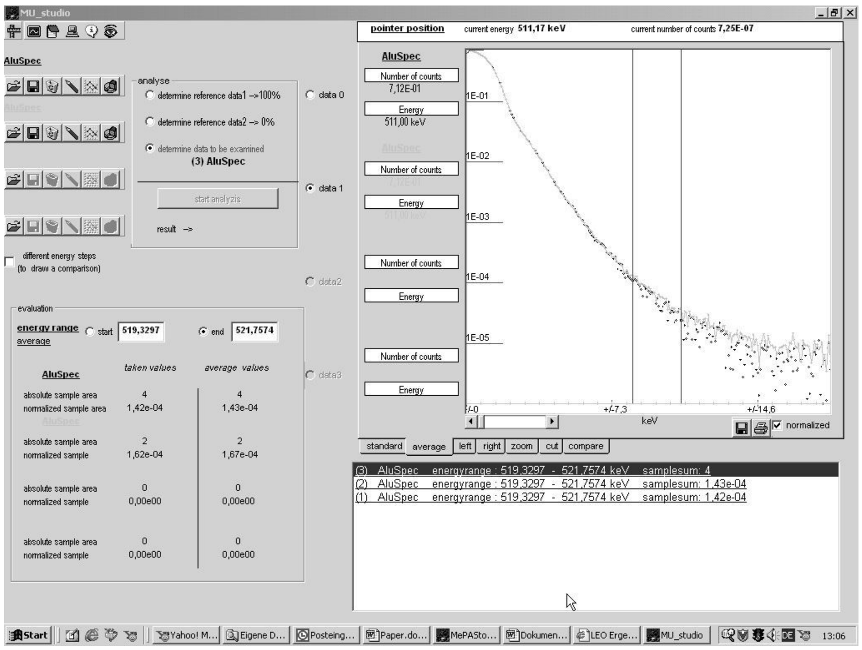

Figure 6 The 'left' and the 'right' halves of the Al coincidence spectrum displayed in Figure 5 illustrated in MePASto's data analysis tool

In addition to the extraction of the coincidence spectrum out of the two-dimensional data field the students integrated data evaluation tools like the numerical integration of the spectra within arbitrary intervals for the determination of line shape parameters or the normalization of the experimental data for the comparison with theoretically obtained annihilation probability densities.

In this project the students immersed themselves in interpolation and picture-processing algorithms, data evaluation and modeling. The fact that they were entrusted with the generation of a tool facilitating a recently developed method in nuclear solid state physics proved to be highly motivating.

Based on the demand to educate the students to high academic standards, the results of a scientific project have to be properly disseminated. In order to provide students with a platform for scientific publications several journals for undergraduate researchers were founded in the last decade. These journals comply with the same directions and quality standards as conventional scientific journals, as for instance a peer review system. In this way students become familiar with scientific writing in early stages of their academic education. Moreover, those journals enable undergraduates to compare their results and achievements globally in a fair and comprehensible way. The outcome of the above mentioned project was therefore written up in a scientific paper and submitted to the American Journal of Undergraduate Research [11]. This additional task was performed by the students in their spare time about three months after having finished their project. The program MePASto is available free of charge and can be downloaded from our department's homepage [12].

Conclusions

The concept of project based learning was introduced at the very beginning of the degree program Automotive Engineering and has proved to be a particularly suitable method to demonstrate the need of mathematics in professional engineering. During the last ten years a coherent procedure has been established in the second and third semester, which familiarises students in a challenging and competitive way with the demands of contemporary industry. Although no statistical evidence of the improvement of our students' appreciation and understanding of mathematics has been compiled, the benefits of our approach are reflected time and again by the quality of the project work they submit. Complementary project based learning enables the students to develop their abilities to adapt new methods to fit new situations. The main aspects seem to be the development of the ability to tackle a task even if there is no predetermined way to find a solution, as well as team competencies and reliability. Furthermore, the projects show the students immediately the value of the just learned methods, thus increasing their attentiveness and their appreciation for the newly learnt topics.

For the implementation of project based learning in the curricula of engineering degree programs lecturers' instructional abilities are critically important as they take on increased responsibilities in addition to the presentation of knowledge.

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