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Toward More Meaningful Laboratory Experiences in Digital Signal Processing and Digital Control

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Abstract–**Digital signal processing and digital control are of utmost importance for electrical engineering students, for they are present in many aspects of today's technical world. Complex topics like these should not be introduced into a curriculum as a crash program, but taken as steps in an evolutionary process. A successful example of this evolutionary process is well underway at the University of Missouri-Rolla.**

I. INTRODUCTION

THREE years ago, the faculty of the Electrical Engineering Department at the University of Missouri-Rolla decided to revise two junior-level circuits courses in order to give them a systems flavor and to introduce the theory and applications of digital signal processing techniques. The responsibility of these two three-semester-hour courses was placed under a "Systems Committee." The immediate change-over was effected by choosing two texts, one for the first semester and the other for the second semester, and patterning the two courses around these texts. The first course consists of the, by now, standard topics of signal and system models–the superposition integral, Fourier series, the Fourier transform and its applications, the Laplace transform and its applications, and an introduction to state variable theory. The second course consists of topics which can be placed under the broad heading "Filtering" and includes analog filters and their properties, the sampling theorem, infinite impulse response digital filters and their design, finite impulse response digital filters and their design, an introduction to the discrete and fast Fourier transforms (FFT) and applications of the FFT.

The underlying philosophy governing these courses has been to emphasize fundamental concepts and to rely on following courses in such areas as controls, communications, and digital filters to emphasize applications. The importance of meaningful laboratory experiences is not being ignored, however, and several efforts to include them at the level of the two fundamental systems courses mentioned above and at the more advanced level of the applications courses which follow are described in this paper.

These laboratory experiences range in complexity from very simple calculator-implemented digital filtering algorithms to more complex experiments involving microcomputer-implemented FFT algorithms for spectral estimation. Implementation of the former type of experience consists simply of a homework assignment, but can be a very meaningful experience for the student. Implementation of the latter type of experience usually involves considerable developmental effort. We have generally found the Master's thesis to be an effective method of doing the groundwork for the implementation of such projects. Another means which we have used for developing software is undergraduate research assistants.

Both types of projects are discussed further in the paper. In addition, we discuss our future goals and the avenues by which we hope to achieve them.

II. EXAMPLES OF DEVELOPED PROJECTS

The laboratory projects developed so far have been concentrated primarily on illustrating digital signal processing techniques, including various types of digital filters, the FFT, and applications. Several of these will now be described.

A. Digital Filters

1. Calculator-implemented IIR filters–A typical classwork assignment given to illustrate the material taught in the second course mentioned in the introduction is the following:

a. Realize a first-order Butterworth filter using the bilinear z-transform assuming a sampling frequency of 100 Hz and a 3 dB cutoff frequency of 10 Hz. Use two scaling techniques: (1) that which matches 3 dB frequencies, and (2) that which provides close low frequency response of prototype and digital filter.

b. Plot the frequency response of both realizations and compare with that of the prototype.

c. Implement this digital filter algorithm as a calculator program. If you do not have a programmable calculator, give the keystroke sequence.

d. Choose a sinusoidal input of $f = 10$ Hz and use the above program to obtain the output for 3-4 cycles. Does your output verify the results of Part b?

This assignment appears rather tedious and may, at first glance, appear to discourage rather than encourage the student. However, in a class of 27 students, all students did the problem to some degree or another, some without programmable calculators. One person did the assignment twice because he was dissatisfied with his first attempt (the in-

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TABLE 1
INPUT AND OUTPUT SEQUENCES FOR A FIRST-ORDER DIGITAL FILTER
(INPUT FREQUENCY = $0.1 f_s = f_{3\,\mathrm{dB}}$)

INPUT	OUTPUT
1.0000	0.2452
0.8090	0.5685
0.3091	0.5639
-0.3909	0.2874
-0.8090	-0.1277
-1.0000	-0.5086
-0.8091	-0.7028
-0.3901	-0.6323
0.3089	-0.3223
0.8089	0.1098
1.0000	0.4995
0.8091	0.6982
0.3092	0.6300
-0.3088	0.3212
-0.8089	-0.1104
-1.0000	-0.4998
-0.8092	-0.6983
-0.3093	-0.6301
0.3987	-0.3213
0.8088	0.1183
1.0000	0.4997
0.8092	0.6983
0.3094	0.6301
-0.3086	0.3213

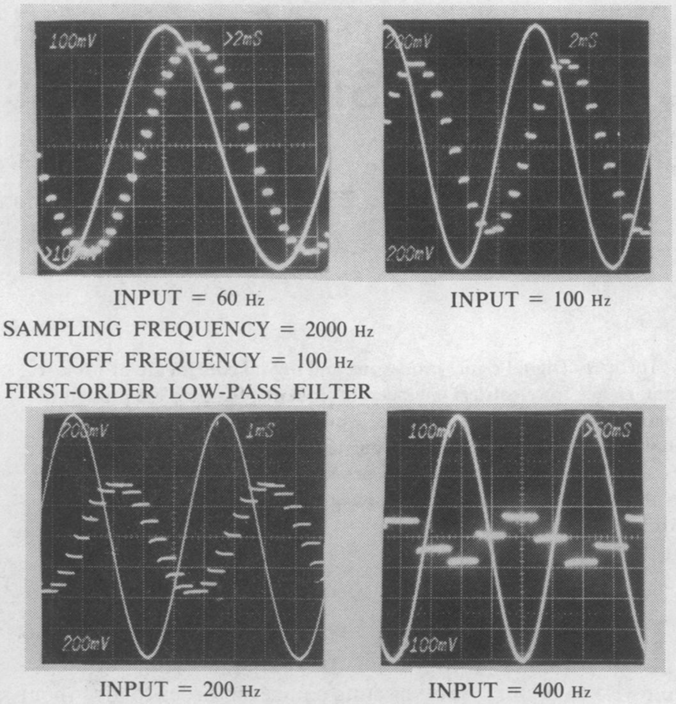
structor did not require him to do it over). Many students enthusiastically reported that they now understood IIR digital filters because they could observe that the algorithm actually implemented a filter. A typical input and output sequence is given in Table I with the input a unity amplitude cosine signal of frequency 10 Hz (0.1 times the sampling rate). From such an input/output sequence, the student can readily see that the output is about 0.7 times the input and phase shifted roughly 0.1^{+} cycles $\simeq 45^\circ$ which he may compare with the frequency response characteristics of the filter.

2. Microcomputer-Implemented IIR Filters—A number of IIR filter algorithms have been implemented on EPROMS for use on an Intel System 80/20 microcomputer with mathboard, A/D and D/A. Depending on the algorithm, the maximum sampling rate ranges from 2000–3000 Hz. So far, first- and second-order low-pass and high-pass Butterworth digital filters have been implemented via the bilinear z-transform. The algorithms employ fixed-point arithmetic. A parameter computation section is included in the program to calculate required filter constants for any cutoff frequency consistent with the sampling rate. This section of the program utilizes floating point arithmetic. Figure 1 compares the input and output oscillograms for several frequencies for a first-order lowpass Butterworth filter. It is apparent that such oscillograms illustrate very graphically the utility of such a filter.

B. FFT and Applications

One vehicle that can be used to gain experience in an area before formal introduction of the material into lecture and laboratory courses is to have Master's theses on related topics. An example of this approach is provided by the following descriptions where three Master's students' theses were focused on fast Fourier transform (FFT) topics using microprocessor-based systems.

1. The first thesis [1, 2] considered the microcomputer implementation of the Cooley-Tukey FFT algorithm (Radix-2) which lends itself rather easily to a combination software and hardware implementation. With a microcomputer as the controller of a data acquisition module and hardware, which computes the butterfly associated with the FFT algorithm, the FFT can be calculated efficiently as shown in Figure 2.



INPUT = 60 Hz
INPUT = 100 Hz

SAMPLING FREQUENCY = 2000 Hz
CUTOFF FREQUENCY = 100 Hz
FIRST-ORDER LOW-PASS FILTER

INPUT = 200 Hz
INPUT = 400 Hz

Figure 1. Input and Output for a First-Order Low-Pass Butterworth Digital Filter.

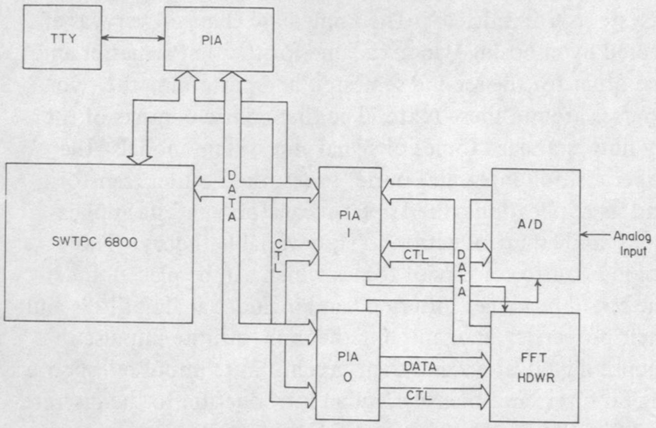
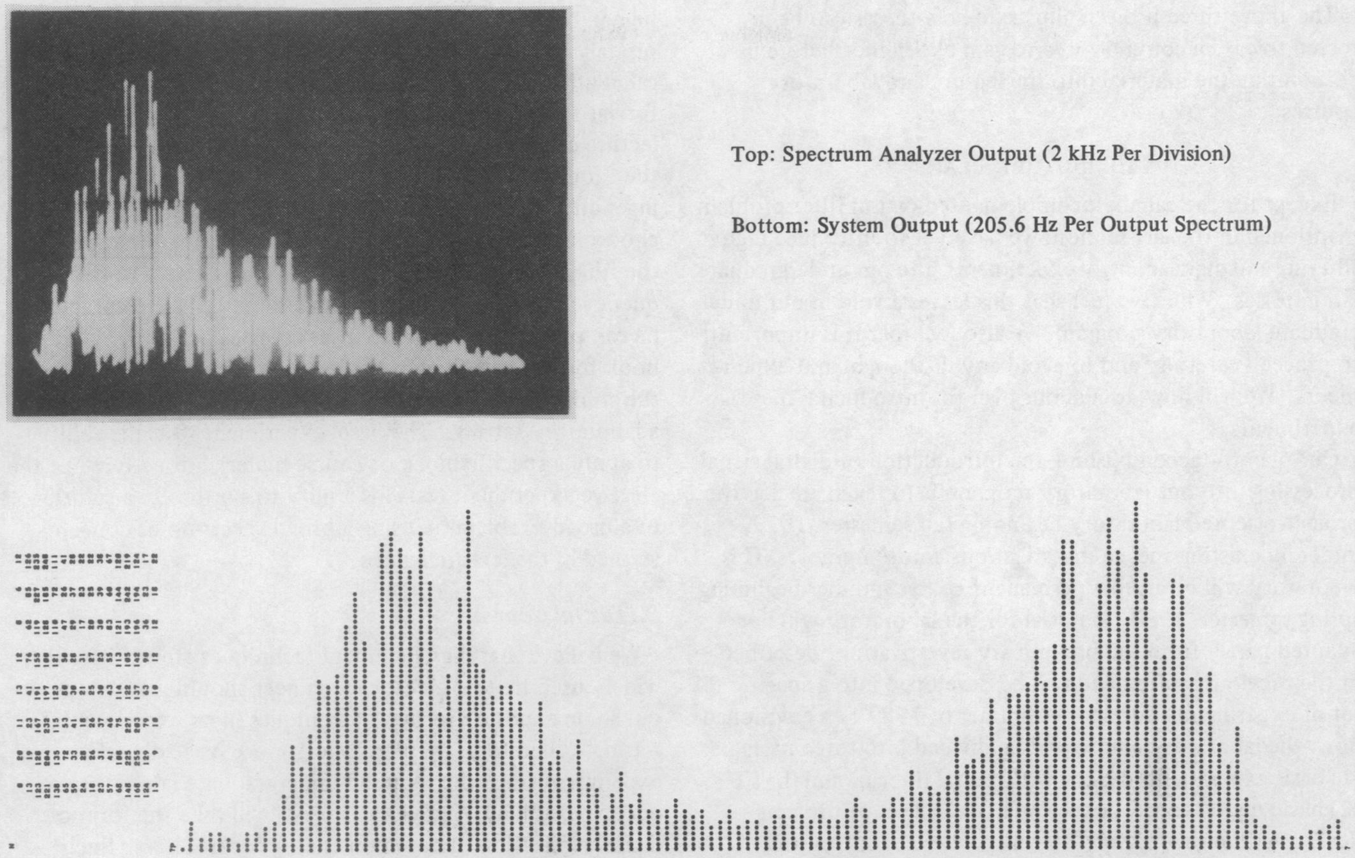


Figure 2. Block Diagram of Microcomputer System.

There are two main sources of error in the above process. One source of error is the quantization error associated with the data acquisition module. The second source of error occurs as the result of the multiplications performed in the calculation of the FFT butterfly. Both errors result because data in a digital computer are represented by a finite number of bits. The effects of such errors can be illustrated to the student by obtaining the FFT of "perfect" sine waves. Any nonzero results for FFT outputs other than the one at the sine wave frequency are due to quantization effects.

2. The second thesis [3] presents a system for determining the FFT which when coupled with a few simple mathematical operations provides an efficient method for estimating the power spectral density of a random time series. The variance



Top: Spectrum Analyzer Output (2 kHz Per Division)

Bottom: System Output (205.6 Hz Per Output Spectrum)

Figure 3. System and Spectrum Analyzer Output with Band-Pass Filtered Noise Input.

associated with using the FFT of only one segment of a time series for estimation of its spectral density is generally unacceptably high. To circumvent this problem, a number of spectral density approximations can be calculated from smaller segments of data and these averaged to form the final estimate. A microprocessor-based system which performs the necessary tasks for formation of an estimate of power spectral density of a time series is the same as shown in Figure 2. An analog signal is sampled, digitized, and stored in the system's memory using an A/D converter controlled by the microcomputer. One small segment of the data at a time is multiplied by a window function and Fourier transformed using a combination hardware-software FFT. The magnitude squared of each frequency sample of each FFT is calculated; these are averaged to form the final power spectral density estimate.

The system offers the advantages of portability, low cost, and versatility. In addition, the output is available immediately without the disadvantage of having to record the signal on magnetic tape for analysis on a general purpose computer. A typical power spectral density for low-pass random noise is shown in Fig. 3.

3. The third thesis [4] presents the results of a simulation of the Gold-Bially FFT algorithm on two microcomputer systems. Using software multiplication, the execution times of the radix-2 and radix-4 on the Futuredata Microcomputer System (Microkit-8/16) are determined for various FFT sizes, showing the superiority of radix-4 over radix-2 for FFT sizes larger than 16 data points. Statistics concerning the number of multiplications, additions, and memory accesses are determined and compared as a function of FFT size. The timing of each subroutine is analyzed, showing that the bottleneck is mostly due to multiplication (see Fig. 4). Replacing software multiplication by a hardware function on the Intel System 80/20 improves the execution speed by a factor of two. Finally a simulation of the Hlywa-Quigley recursive FFT (RFT) [Ref. 4] algorithm proved that, if only part of the full spectrum is needed, the RFT is faster than the FFT, especially for large FFT sizes.

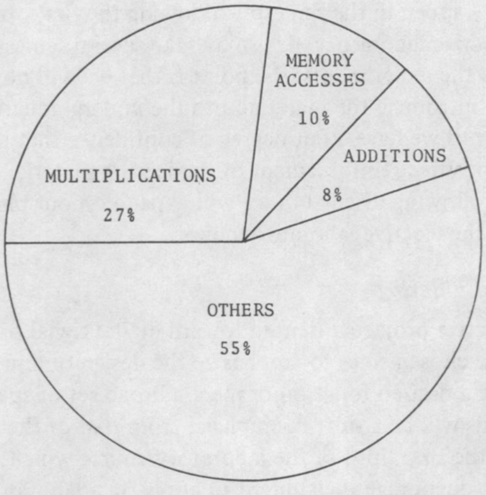


Figure 4. Time Spent in One Typical FFT.

The above three projects illustrate how theses can be directed toward a common area to gain experience before incorporating the material into the lecture and laboratory courses.

III. FUTURE PLANS

Except for the calculator-implemented digital filter problem mentioned in the last section, we have yet to introduce digital filtering and digital control experiments into our undergraduate laboratories. While we feel that this leaves a void in our undergraduate laboratory program, we also feel that it is important to proceed carefully and to avoid any ill-thought-out experiments. We will now discuss our plan for introducing these experiments.

Our plan for accomplishing the introduction of digital signal processing into our laboratory program is to teach an elective project-oriented laboratory beginning fall semester, 1979, under an existing special investigations course number. This laboratory will be given a permanent course number beginning spring semester, 1980. Material for the laboratory will be adapted partly from the preliminary investigations described in the previous section and will be developed into a specific set of experiments during the summer of 1979. As envisioned now, the laboratory course will be divided into three parts: (1) basic experiments dealing with digital filtering and the FFT; (2) basic digital control experiments; (3) a set of projects dealing with either digital filtering or digital control, the selection of which is left partly to the student. Eventually appropriate laboratory experiments will be adapted from the elective course into the undergraduate laboratory program. This may happen in the semester following the first offering of the elective laboratory, or it may take several semesters to introduce the experiments; the point is that we will not be forced to introduce the material into the undergraduate laboratories until we have a fair degree of confidence that it will produce positive reinforcement of the lecture material.

In the following discussion we will expand on our philosophy for the elective laboratory course.

A. Digital Filtering

The elective projects oriented toward digital signal processing will be chosen so as to emphasize the design of a processor to achieve a desired function or meet a broad set of specifications. This will be a shift in emphasis from that of the experiments in the first third of the laboratory course which will be written to encourage the student to apply, in a laboratory setting, the textbook concepts learned in the lecture course. As an example to illustrate the difference between these two paths of emphasis, an experiment employed to emphasize basic course concepts might consist of measuring the amplitude and phase response characteristics of a second-order Butterworth digital filter with a given cutoff frequency and for a given sampling rate which has been realized by a specific procedure (e.g., bilinear z-transform of a prototype transformation). On the other hand, in an elective experiment the student might be asked to design a filter which meets certain amplitude and phase response specifications. In both cases, he will be able to use preprogrammed algorithms with appropriately chosen filter constants. In the basic experiment, the calculation of the filter coefficients proceeds in a straightforward manner using specific equations developed in the lecture course. In the elective experiment the calculation of the filter coefficients is preceded by a test of the student's ingenuity in selecting an appropriate realization technique, choosing a satisfactory prototype filter, fixing the order of the filter properly, and choosing an acceptable cutoff frequency and a sampling rate. Once these tasks are completed, he can proceed to calculate filter coefficients using the textbook formulas learned in the lecture course. In both cases, the student's main benefit is applying textbook concepts in a laboratory setting. The basic experiment tests his ability to apply a specific block of course material directly while the elective experiment tests his ability to synthesize a solution to a broad problem by using a broad spectrum of concepts learned in the lecture course.

B. Digital Control

We believe that digital control techniques are sufficiently widely used that no electrical engineer should graduate without some exposure to these techniques in an experimental setting. Therefore, we plan to introduce basic digital control experiments into the required undergraduate laboratory sequence. Initially, these experiments will take the form of digital realization of common analog control laws. Such control laws are commonly used in industrial processes, and they provide a convenient point of departure for those students already familiar with continuous-time control systems. The experiments will use a microprocessor system for digital computation. A "black box" approach will be used. That is, digital filter and control algorithms will be preprogrammed and available to the student on Read Only Memory (ROM). The student will simply input algorithm parameters. This approach releases the student from the burden of assembly language programming and maximizes the time spent investigating the material of interest. The process to be controlled will be simulated on an analog computer. Our students are already familiar with analog simulation; therefore, this approach minimizes equipment setup time and requires no additional capital expenditure. Later we expect to introduce simple direct digital control experiments utilizing readily available hardware, e.g., stepping motors.

At a somewhat more advanced level, we plan to participate in the elective Digital Filtering/Digital Control laboratory already mentioned. This laboratory will contain more advanced digital control experiments and some elective projects. Initially, it will be used to thoroughly test the basic experiments already discussed before introducing them in the required laboratory program. Projects will consist of designing digital controllers and compensators to meet various transient and steady-state performance specifications. As we gain experience with the laboratory, we hope to introduce some additional hardware projects and one or two projects relating to multivariable systems. These latter projects will probably require use of the department's Data General NOVA 800 minicomputer. We plan to offer the laboratory on an experimental basis during the fall semester, 1979, and anticipate one or two digital control experiments will be placed in the required undergraduate laboratory program by the fall of 1980.

IV. SUMMARY

We currently have no required experimental work in digital filtering and digital control at the undergraduate level. We strongly believe we must act to rectify this situation as rapidly as possible. However, we do not favor a crash program. Rather, we prefer an evolutionary one in which experiments are thoroughly tested and revised as necessary before being introduced into the undergraduate laboratory program. Eventually we hope to introduce three to six required digital control experiments and a one-credit-hour elective laboratory containing meaningful digital filtering and digital control design projects.

In developing this elective laboratory, we plan to rely heavily on previous developmental work carried out in digital signal processing by means of several vehicles. These were described in Section II. Only through this careful step-by-step process do we feel confident that meaningful laboratory experience in digital signal processing and digital control can be provided to our students.

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An Integrated Approach to Minicomputers and Microcomputers in Electrical Engineering Laboratories

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***Abstract*—This paper describes the integration of minicomputers and microcomputers into the general laboratory experience of an Electrical Engineering student. Considerations in the planning of a laboratory building to allow data lines to be installed are pointed out. A detailed description of the computer laboratory facilities is given. The traditional involvement of the small scale computer in engineering education is reviewed. The nontraditional implementation of the small scale computers in laboratory classes is described in detail. It involves concepts such as data collection and processing, automated test, and process control. Along with these concepts, plans should include a real-time operating system along with minicomputers and microcomputers capable of real time operation. The software generated for integration of this computer system in the laboratories should be modular for easy expansion and should be easy to use. This avoids discouragement of students who lack computer sophistication, but also allows early involvement.**

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INTRODUCTION

THE Department of Electrical Engineering, as a part of the College of Engineering at Wichita State University, owns and operates a minicomputer and microcomputer laboratory system. The primary purpose of this system is for the training of students in the use of a small scale computer as a laboratory instrument and for research which requires these special facilities. It operates in a hands-on environment with only a minimum of student help required as operations resources. It is not intended that this computer laboratory serve as a facility for learning programming, although that also must be taught, but as a facility dedicated to the task of being an Engineering Laboratory instrument. It is currently being used by students for real time signal sampling, digital filtering of signals, circuit analysis, spectral analysis of collected data, and graphic display of data. This system is also used for various research projects such as picture processing, speech signal processing and the wind power data processing.

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