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# A Low Cost Laboratory for Enhanced Electrical Engineering Education

Ciira wa MAINA[1], Asaph MUHIA[2], James OPONDO[3]
[1,3]*Dedan Kimathi University of Technology, P.O. BOX 657-10100 Nyeri, Kenya,*
[2]*Jomo Kenyatta University of Agriculture and Technology,*
*P.O. Box 62,000 – 00200 Nairobi, Kenya*
[1]*Email: ciira.maina@dkut.ac.ke*

**Abstract:** This paper presents low cost laboratories that aim to enhance the teaching of electrical and electronic engineering. The laboratories have been designed and developed based on the Raspberry Pi microprocessor system and are aimed at exposing students to the integration of software and hardware in electrical engineering in addition to ensuring that students appreciate the theoretical foundations of areas such as digital signal processing and instrumentation. The paper describes the laboratory exercises developed. Feedback from students was collected and analysed. The positive response shows the effectiveness of this approach in teaching electrical and electronic engineering.

**Keywords:** Raspberry Pi, Low cost Laboratory, Digital signal processing, Instrumentation.

## 1. Introduction

It is widely accepted that for any country to develop, it must industrialize. This industrialization is often driven by a vibrant manufacturing sector which in turn is supported by skilled engineers. It therefore follows that for any developing country to improve the well being of its people, it must train an adequate number of engineers. In [1] the authors argue that economic development for developing countries can be effectively stimulated by building the technical capacity of their workforce through quality engineering education programs. Despite this fact, engineering education in Africa is not well funded [2] leading to a small number of engineers per capita in Africa compared to developed economies [3].

Engineering departments must compete for scarce education funding and it is therefore important for the various engineering disciplines to device low cost laboratories which can be used to train future engineers. A number of researchers have investigated the development of low cost electrical engineering laboratories. For example in [4] Yair Linn presented a low cost wireless communication laboratory based on field programmable gate arrays (FPGAs). In [5] James Rehg presents a low cost trainer for flow control aimed at improving the understanding of control engineering concepts. In both cases, the laboratory exercises were found to be adequate in delivering the desired content at low cost

In the recent past, advances in electronics have made electronic devices which were prohibitively expensive a decade ago very accessible. For example, mobile phones are now within reach of a large segment of the African population when just a few years ago very few people had a mobile phone. An additional benefit of this revolution in electronics is that a number of microcontrollers and microprocessors are now within the reach of students and hobbyists. This has led to an effort to use these devices within the electrical engineering curriculum so as to improve the quality of laboratory exercises performed by students particularly in developing countries.

This paper describes efforts to introduce a cheap microprocessor, the Raspberry Pi, into the electrical engineering curriculum at Dedan Kimathi University of Technology (DeKUT) in Nyeri, Kenya. The Raspberry Pi (RPi) is an affordable and powerful microprocessor capable of performance similar to a modern personal computer. In addition to its considerable processing power, it is small in size, about the size of a credit card (see Figure 1). The RPi also has a number of general purpose input-output (GPIO) pins which allows it to be connected to a number of sensors. This makes the device ideal for embedded systems and systems which require on-board processing.

We focused on two courses, namely, Digital Signal Processing (DSP), and Instrumentation and based on the results of this first phase, we intend to develop labs for additional courses in future.


*Figure 1: The Raspberry Pi model B+. A Kenyan Bank card is shown for comparison.*

## 2. Objectives

This work is aimed at improving electrical engineering education by developing laboratory exercises based on affordable microprocessors. It is hoped that if the laboratory exercises proposed here are widely adopted, engineering students will have a firmer grasp of key electrical engineering concepts. The main objectives are to:

1. Develop and implement laboratory exercises for electrical engineering courses based on the Raspberry Pi.
2. Improve the understanding of important electrical engineering concepts using hands on laboratory exercises.
3. Develop outreach programs to encourage primary and secondary school students to consider electrical engineering.

## 3. Methodology

Engineering students are expected to have an understanding of several hardware and software concepts. For students to understand these concepts they must perform hands-on laboratory exercises. Unfortunately, due to the costs involved in purchasing the necessary equipment, students in developing countries sometimes miss out on this critical component of an engineering education. Using DSP and Instrumentation as examples, we describe some fundamental concepts and illustrate how laboratory exercises based on the RPi can be used to explain these concepts.

 

### *3.1 Digital Signal Processing*

The aim of the DSP course is to introduce a number of fundamental concepts including:

1. Discrete time signals and systems in the time and frequency domains
2. Linear time invariant systems
3. Sampling of continuous time signals
4. The discrete Fourier transform

In order to motivate the study of these concepts a laboratory based on the manipulation of speech signals was designed.

Speech is arguably the most accessible digital signal available and it makes sense to use the manipulation of speech signals to explain DSP concepts. Using a microphone connected to the RPi, the student can record his own voice and use appropriate software to manipulate it. This introduces higher concepts such as parameter estimation from signals. In this work we use the estimation of fundamental frequency since it is a simple parameter to estimate from speech and it can be used to classify the gender of the speaker.

#### *3.1.1 Software Setup*

The computing environment used in this laboratory exercise was the Raspbian operating system - Debian Wheezy. This operating system is quite similar to Ubuntu. The labs were based on Octave, which is very similar to MATLAB, and made use of other open source tools such as SoX, the Swiss Army knife of sound processing programs. Installation instruction are available on the project website http://sox.sourceforge.net/. The exercises were tested on Octave version 3.6.2.

#### *3.1.2 Speech Processing*

Several applications require the analysis of frequency content of signals. In continuous time signals this is achieved using the Fourier series (for periodic signals) or the Fourier transform (for aperiodic signals) [6]. In real world applications continuous time signals are first discretized before they are analysed. In this case we use the Discrete Time Fourier Transform (DTFT) to analyze the signals. The DTFT is a sampled version of the frequency spectrum of the sampled signal and it is efficiently implemented using the Fast Fourier Transform (FFT) [7].

To compute the frequency content of the speech signals we divide the signal into short overlapping segments of about 32ms. Over this duration, it is assumed that the properties of the speech signal remain stationary. We then compute the DTFT of the segments and obtain a sampled version of the spectrum (In general this is a complex function and we must plot both the magnitude and phase for a complete representation. In speech applications we often ignore phase and work with the magnitude spectrum). This produces a 2-dimensional image known as a *spectrogram*. Figure 2 shows a spectrogram obtained from a recording of the first author saying “moja”, the Kiswahili word for “one”. It is obtained from a 2s recording sampled at 16kHz. It appears as a heatmap with high values represented by deep red and low values deep blue. Intermediate values appear yellow. From this spectrogram we see that the word is spoken in the interval between 0.8s and 1.4s. If we extract the segment at 1s corresponding to 32ms (512 samples at 16kHz) and compute it's DTFT we obtain the results shown in Figure 3. We see that most of the spectral content is below 1 kHz.

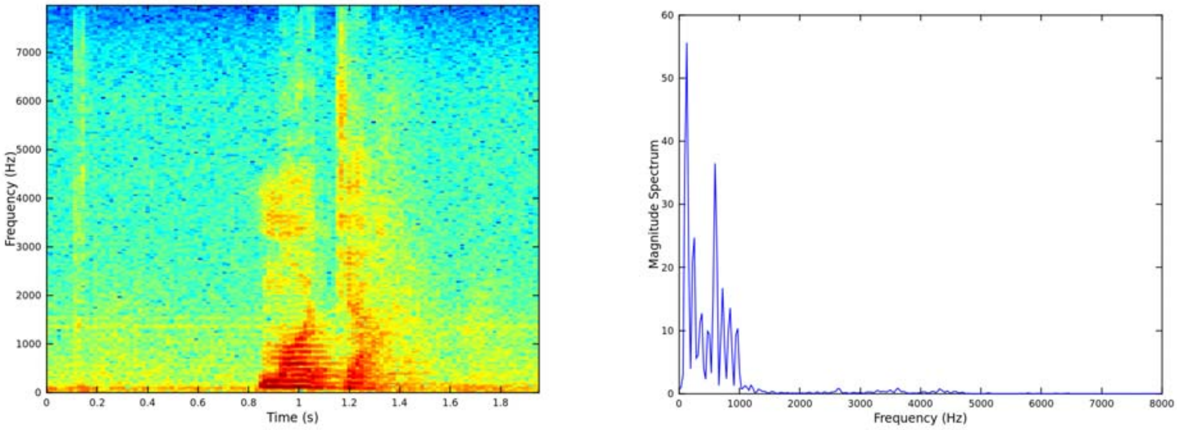


*Figure 2: A spectrogram of the word "Moja" (left) and*
*the magnitude spectrum of a speech segment at 1s corresponding to 32ms (right)*

### *3.1.3 Fundamental Frequency Estimation*

It is often important to estimate the pitch of speech signals. To achieve this, we estimate the fundamental frequency of the speech signal also referred to as F0. A popular method for estimation of F0 is based on the autocorrelation function (ACF) [8]. Due to the simplicity of this technique, it is well suited to an introductory laboratory on the estimation of a parameter from a speech signal.

The ACF of a periodic function has peaks whose spacing is equal to the period of the signal. This is illustrated in Figure 3 for a periodic sine wave. To apply this method to a speech signal, we compute the ACF of a finite duration signal corresponding to a short speech segment (32ms in this case). Over this short segment the characteristics of the signal can be assumed to be stationary. Figure 4 shows the speech signal and ACF of a speech signal obtained from the first author vocalising the word "moja" which means "one" in Kiswahili. From the plot of the ACF we see that the first non zero peak is obtained at approximately 0.01s which corresponds to an estimate of $F0$=100Hz.

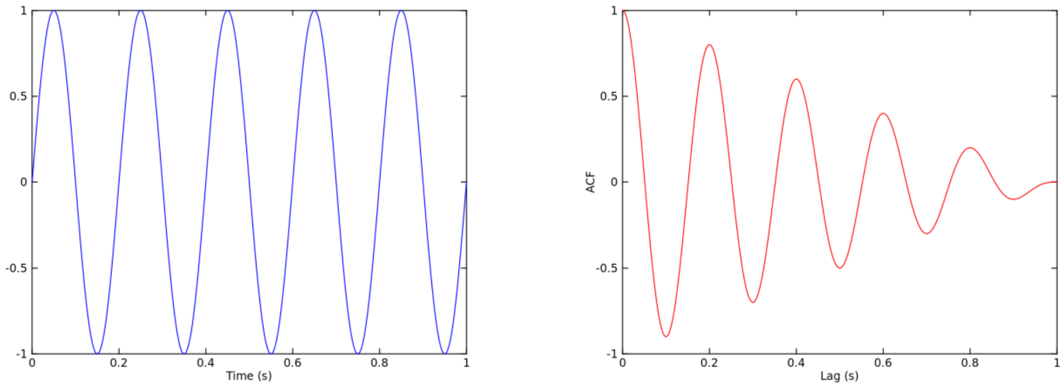


*Figure 3: A periodic sine wave (left) and the corresponding autocorrelation function (right).*

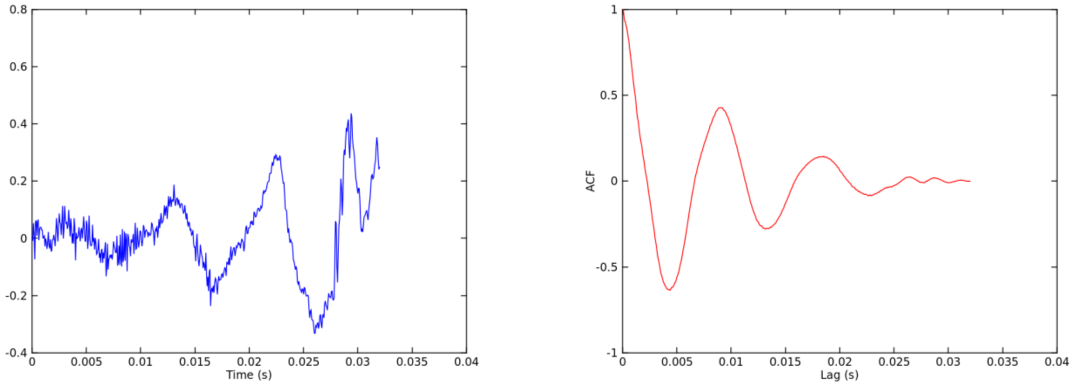


*Figure 4: Speech waveform (left) and the corresponding autocorrelation function (right).*

#### *3.1.4 Laboratory Exercises*

To introduce the students to DSP and speech processing, three laboratory exercises were developed, namely:

1. Laboratory 1: Introduction to Octave
2. Laboratory 2: Speech in the time and frequency domain
3. Laboratory 3: Estimation of Fundamental Frequency

We started by reviewing fundamental programming concepts such as variables, flow control, and functions using Octave as the programming environment to ensure the students would be able to write their own programs to analyse speech signals in the subsequent labs.

In laboratory 2, the students were expected to use the Raspberry Pi with SoX installed to record their own voice using a cheap USB microphone and display the signal in both the time and frequency domain. In laboratory 3, we introduced the students to parameter estimation from speech signals using estimation of fundamental frequency.

For effective dissemination of laboratory manuals to the students, we used a project wiki. The lab manuals were made available on the project wiki before the lab was conducted. These manuals are publicly available and can be downloaded from the project wiki http://raspberry.kenet.or.ke/index.php/Digital_Signal_Processing.

### *3.2 Instrumentation*

The aim of the instrumentation laboratory in this work is to equip the student with important skills in the use of microprocessors in remote sensing, signal processing, storage and display in instrumentation systems [9]. Remote force measurement and recording is chosen as the typical application. A strain gauge is used for force measurement and a signal conditioner that comprises of an amplifying circuit and an analog to digital converter is wired. The digital equivalent of the force measured is read via a program written in Python. A WiFi network is used for transmission of the digital output from the remote location to the central control room. A database developed using mySQL is finally used for data storage.

#### *3.2.1 Laboratory Exercises*

In instrumentation, three laboratory exercises were developed, namely:

1. Laboratory 1: Introduction to Python Programming
2. Laboratory 2: Analogue to Digital Conversion
3. Laboratory 3: Real-time Remote Force measurement and recording

As was the case with the DSP labs, we started by introducing students to the computing environment. Here, Python was chosen as the programming language. Lab 2 was designed to introduce students to measurement of analog quantities of interest using the Raspberry Pi. Most of signals from sensors are analogue in form. However, the Raspberry Pi handles only digital signals as it has no inbuilt analogue to digital converter. This necessitates use of an analogue to digital converter to handle analog signals. In this laboratory, we use the MCP3008 analogue to digital converter chip which is a 10 bit, 8 channel IC. A variable resistor is used as the source of the analogue signal and is connected to a 5 V source. The analogue input (0 to 5 V) is fed to one of the 8 channels of the MCP3008. By adjusting the variable resistor, different values of analogue voltages are used for testing the converter. The output (digital equivalent in decimal form) is displayed on the monitor. In lab 3, the students are introduced to real time remote measurement.

All the laboratory exercises had accompanying manuals which described the procedure to be followed and the equipment required. The lab manuals were made available on the project wiki before the lab was conducted. These manuals are publicly available and can be downloaded from the project wiki http://raspberry.kenet.or.ke/index.php/Instrumentation.

## 4. Technology Description

The laboratory exercises described in this paper are based on the Raspberry Pi (RPi) microprocessor which is a cheap and small size computer. It is ideal for computational tasks and interfacing with hardware and this makes it suitable for teaching electrical engineering courses which have both hardware and software components such as digital signal processing and instrumentation. For this work, we used the RPi model B+ which has the following specifications:

1. 40 GPIO pins
2. 4 USB ports
3. Ethernet port
4. Based on the BCM2835 Broadcom chip

In addition to the cheap computer, the labs make use of open source software. This makes the labs affordable for implementation in developing countries. For example we make use of Octave (https://www.gnu.org/software/octave/) which is an open source alternative to Matlab.

## 5. Results

The DSP and Instrumentation labs were successfully delivered to the students at DeKUT in the first semester of the 2015/2016 academic year. For each of the labs, students were expected to write a report giving details on how they performed the labs and the results obtained. Based on evaluation of these reports, the laboratory exercises went well.

### *5.1 Student Evaluation*

For the DSP labs, we conducted an anonymous online survey to obtain feedback from the students. In total, 81 students performed the labs. 24 students filled in the questionnaire and their responses were analysed. The questionnaire can be viewed here https://www.surveymonkey.com/r/YX9VLPQ. The questions asked were in form of statements which required respondents to agree or disagree with them. The degree of agreement or disagreement was mapped to a 1-5 scale with 1 representing strong disagreement and 5 representing strong agreement. The questions and the weighted average scores are shown in Table 1.

*Table 1: Results of the anonymous online questionnaire administered to analyse the laboratory exercises.*

| # | Question | Weighted Average |
|---|---|---|
| 1 | The laboratory exercises motivated me to study the material taught in class | 4.08 |
| 2 | The laboratory manual was clear | 4.21 |
| 3 | I would recommend similar laboratory exercises to be developed for other courses | 4.50 |
| 4 | I was able to obtain assistance whenever necessary to perform the laboratory exercises | 4.33 |
| 5 | The laboratory exercises were enjoyable to perform | 4.21 |
| 6 | The following laboratory exercises were useful<br>I. Laboratory 1: Introduction to Octave<br>II. Laboratory 2: Speech in the time and frequency domain<br>III. Laboratory 3: Estimation of Fundamental Frequency | <br>4.29<br>4.30<br>4.25 |
| 7 | The following laboratory exercises were successfully completed<br>I. Laboratory 1: Introduction to Octave<br>II. Laboratory 2: Speech in the time and frequency domain<br>III. Laboratory 3: Estimation of Fundamental Frequency | <br>4.42<br>4.21<br>3.92 |
| 8 | My understanding of the following digital signal processing concepts improved after performing the laboratory exercises<br>I. Sampling<br>II. Discrete Fourier Transform<br>III. Autocorrelation<br>IV. Fundamental Frequency Estimation | <br>4.38<br>3.87<br>3.61<br>3.57 |

The survey also gave the students an opportunity to give general comments on the lab. Some example comments include (The comments have been edited for clarity):

1. "[I]t was one of the greatest activity [I] have ever done in [K]imathi university"
2. "[T]he laboratory exercise was well scheduled, interactive as each student would work with his own raspberry pi and the instructions were well laid out"
3. "This was one of the best lab[s I] have undertaken in the university, possibly because [I] had to do it alone unlike the group labs."
4. "It was amazing to interact with [the] raspberry pi"
5. "The exercises were good and I enjoyed every bit of each. I would recommend the same be applied in other courses as well."
6. "[T]he laboratory manuals were well fashioned for us but the autocorrelation labs were not clear as we did not understand its use in digital signal processing"

As we can see from the comments, the laboratory exercises were well received by the students. The comments will be very useful in updating and improving the laboratory exercises. For example, it was observed that a number of students found the concept of autocorrelation difficult to understand and therefore did not successfully complete lab 3. In future we, will try to make this concept clear.

## 6. Business Benefits

Most of the equipment used for electrical engineering labs are generally big in size, complicated and expensive. The Raspberry Pi based labs are small and simple to implement and students can carry them around. Due to their low costs, they can be available in very many sets, meaning that students can carry out the labs in smaller groups and even as individuals. This has the potential to reduce the cost of electrical engineering education making it more cost effective for universities and students.

In addition, the Raspberry Pi is suitable for the design and implementation of a wide range of engineering systems for example home automation systems. Students participating in the laboratory exercises described in this paper can design and implement systems which can be sold to provide income. By encouraging engineering students to develop their own solutions to local problems, we can reduce the problem of unemployment among engineering graduates.

## 7. Conclusions

In this paper we have presented low cost laboratory exercises based on the Raspberry Pi microprocessor aimed at improving electrical engineering education in developing countries. In particular we focused on two courses that are very important in the electrical engineering curriculum namely digital signal processing and instrumentation. The labs were delivered to students at Dedan Kimathi University of Technology during the first semester of the 2015/2016 academic year. The laboratory exercises emphasize the link between software and hardware in implementing engineering systems. In addition, the laboratory exercises are designed to be hands on with the students involved in both connecting the hardware components and writing appropriate software. Based on the evaluation of the labs through an anonymous online survey, we found that the labs were well received by students and led to improved understanding of key engineering concepts.

Future work will extend these laboratory exercises to other courses in the engineering curriculum. In addition, we plan to explore outreach activities to local primary and secondary schools to encourage students to pursue careers in science, technology, engineering and mathematics.

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