Enhancing a Real-time Audio Laboratory Using the MATLAB Audio System Toolbox

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Abstract

Audio output as part of laboratory experiments provides students with tangible motivation and a way in which to experience the impacts of signal processing first-hand. This paper presents an upgrade in a sophomore-level signal processing laboratory course by implementing The Mathworks,® Inc. MATLAB® Audio System Toolbox™ for real-time audio applications. The course in which this upgrade was implemented is required of all engineering majors and provides a foundation in the mathematical modeling and analysis of signals and of linear time-invariant systems. The laboratory component of the course utilizes applications of signal processing to motivate the breadth of the field which includes filters, AM modulation, and Nyquist sampling theory. The MATLAB® Audio System Toolbox™ implemented in this study replaces both the TMS320C6713 DSK (225 MHz) development board and the more recently examined Beagleboard-xM (1 GHz) board. Comparisons are made between these three platforms.

This study was carried out by assessing both student and instructor observations and laboratory completion time using the Audio System Toolbox versus the TI-DSK board over four key laboratory experiments: Digital Audio Effects, Touch-Tone Phone, Voice Scrambler-Descrambler, and Sampling and Aliasing. When comparing student satisfaction levels, we found a statistically significant improvement ($p \approx 0.10$) when students used the Audio System Toolbox™ over the TI-DSK board and showed no negative effect on the logistics of integration or usage, as reported by the students and laboratory teaching assistants. The motivation for this work comes at a time when real-time hardware for signal processing is becoming integrated into more multi-versatile computing platforms not necessarily dedicated to the task. In addition, the speed and memory of on-board computer microprocessors with audio outputs provides the resources necessary to realize audio processing real-time in the teaching laboratory environment. While the on-board computer microprocessors are not as robust as specialized external counterparts, their use has great impacts on classroom and learning potentials.
Introduction

Studies have shown that the best choice for laboratory exercises in an undergraduate signals & systems curriculum are ones that emphasize concepts related to signal processing by offering a relevant, real-world design experience.\textsuperscript{1,2} These types of practical implementation have been shown to enhance learning and achieve better outcomes. Courses that have successfully implemented real-time signal processing to solidify concepts introduced in class lectures have largely employed hardware-based solutions in order to provide a hands-on approach to in-lab learning.\textsuperscript{1,3,4,5,6,7} These hardware-based signal processing laboratories have had marked success in providing hands-on, realistic lab experiences to undergraduate students in an Electrical and Computer Engineering (ECE) curriculum.\textsuperscript{1,7} The development of such laboratories for a required introductory signal processing course has demonstrated that application-based exercises illustrating the fundamental signal processing concepts using a DSP hardware platform have been well received.\textsuperscript{7} A secondary advantage of using this hardware is that it introduces students to tools that they will be able to use in senior design courses and after graduation. However, with the advent of highly capable multi-core processors as well as application-oriented software programs, real-time signal processing can be achieved at a very accessible level by using the computational hardware already present in modern day computers.

The work presented here leverages and expands upon prior work done using a hardware-centric approach to real-time signal processing in an undergraduate signals & systems course.\textsuperscript{4} In it, an upgrade was made to the laboratory experience by implementing the MATLAB\textsuperscript{R} Audio System Toolbox\textsuperscript{TM} for laboratories involving real-time audio applications. The course in which this upgrade was implemented is required of all engineering majors and provides a foundation in the mathematical modeling and analysis of signals and of linear time-invariant systems. The laboratory component of the course utilizes applications of signal processing to motivate the breadth of the field which includes filters, AM modulation, and Nyquist sampling theory. The Mathworks,\textsuperscript{R} Inc. MATLAB\textsuperscript{R} Audio System Toolbox\textsuperscript{TM} implemented in this study replaces both the TMS320C6713 DSK (225 MHz) development board (shown in Fig. 1) and the more recently examined Beagleboard-xM (1 GHz) board. The course studied here is typically taken by sophomore or junior level students in both the ECE and Biomedical Engineering (BME) fields. In the course, MATLAB\textsuperscript{R} software with the SIMULINK toolbox is used. All ECE majors and BME students double-majoring in ECE are required to enroll in this core signal processing course. The laboratory in which these experiments is conducted consists of 14 stations each equipped with 1) a PC with microphone, speakers, and headphones and 2) test and measurement equipment including a function generator, digital oscilloscope, multimeter, and power supply. Students are also given access to various audio cables, microphones, and headphones. Figure 2 shows typical workstations for using the DSK board or the Audio System Toolbox.\textsuperscript{TM}

Prior to the course being offered with both the MATLAB\textsuperscript{R} Real-Time Audio Toolbox\textsuperscript{TM} and the standard C6713 DSK hardware, the Audio System Toolbox\textsuperscript{TM} laboratory exercises were updated and re-tested to include new instructions and example images so that they were compatible with the software. Otherwise, no changes were made to the labs so that students using either platform would have an equivalent lab experience including the same measurements, questions, and assignments.
Four laboratories in the course implemented the use of real-time audio: Real-Time Digital Audio Effects, Dual-Tone Multi-Frequency Touch Tone Phone, Sampling and Aliasing, and Voice Scrambler-Descrambler. These labs provide a foundation in the mathematical modeling and analysis of signals and of linear time-invariant systems. The laboratory component of the course utilizes applications of signal processing to motivate the breadth of the field which includes filters, AM modulation, and Nyquist sampling theory. The following list details the major concepts introduced in each laboratory exercise:

- **Real-Time Digital Audio Effects**—sampling rate, difference equation representation, and block diagram implementation in SIMULINK. In this laboratory students manipulate audio signals so that they can see and hear the effect of various algorithms.

- **Dual-Tone Multi-Frequency Touch Tone Phone**—correlation, signal transmission, and telephony. Sinusoidal signals are translated into numbers on an LED “keypad” or display.

- **Sampling and Aliasing**—speech coding and decoding, fixed sampling rate, Nyquist criterion. Real-time voice signals are transmitted and sampled with auditory feedback.

- **Voice Scrambler-Descrambler**—modulation, demodulation, anti-aliasing. In this laboratory speech or music is anti-aliased using filter design.

In the Spring 2017 and Summer 2017 semesters, when the Audio System Toolbox™ was introduced, 67 and 11 undergraduate students were enrolled in the two offerings of the course, respectively. There were 7 laboratory sections each week in the Spring semester and 1 laboratory section in the Summer. For the four laboratories involving the use of a DSP hardware platform, students in 2 (22 students) of the 7 lab Spring sections and all (11 students) in the Summer lab section used the MATLAB® Audio System Toolbox;™ the remaining groups, in the Spring only, used the existing TI C6713 DSK platform. The 33 students who used the real-time Audio System Toolbox™ represent 38% of the class overall (Spring and Summer semesters combined) or 30% of the class in the Spring and 100% of the class in the Summer.
Motivation

As reported in prior work, the main motivation to pursue a new platform for the real-time signal processing laboratories in this undergraduate signal processing course stemmed from the desire to eliminate outdated Texas Instruments Code Composer Studio v3.3 software which relies on the Windows XP operating system and is no longer supported by the Microsoft Corporation. In addition, leveraging the powerful computing capabilities present in newer desktop hardware in lieu of hardware-based solutions provided impetus for a new platform.

Every educator in engineering knows that with the benefits of hardware come the challenges of interfaces. A great deal of time can be spent troubleshooting hardware rather than devoting it to students’ understanding of concepts. Alternatives for real-time audio signal processing were sought out, especially ones that would reduce the complexity of usage but still provide sufficient utility to implement all existing laboratory exercises. One major motivator was to retain the MATLAB® software in the course as it is a common platform already being used throughout the undergraduate engineering curriculum. The MathWorks, Inc. developed the Audio System Toolbox™ in 2016 to provide “algorithms and tools for the design, simulation, and desktop prototyping of audio processing systems.” It allows real-time signal streaming through native computer audio jacks using either MATLAB® software directly or within a MATLAB® SIMULINK block. It includes libraries for filtering, equalization, dynamic range control, and reverberation. Since the lab exercises involving real-time audio already depended on the use of SIMULINK to create block diagram models, implementing the new Audio System Toolbox™ using existing software and still obviating the need for an intermediate compiler—an issue that plagued the TI DSK board hardware in the form of Code Composer Studio—proved to be a timely and viable option. Moreover, since the university license to use MATLAB® was already in place, the addition of the Audio System Toolbox™ required only a software request that the package be added to the standard suite and came at no additional cost.
The observations collected in this study are based on a survey completed by students at the end of the semester regarding their learning experiences as part of the course. Additional data was sought from the laboratory teaching assistants. The laboratory teaching assistants took notes after each laboratory exercise indicating overall comments and impressions as well as lab time to completion by student groups.

Data was collected on the following quantitative metrics: the average time it took for each group to complete the laboratory exercise, the total number of questions asked by students during lab, and how difficult the exercise was for students on a scale from 1–10.

**Methods and Implementation**

Two separate—but identical in terms of content—procedures were used to conduct laboratory experiments as part of this study. The standard procedure for the laboratory exercises was to use the SIMULINK software in conjunction with the Texas Instruments’ C6713 DSK board and Code Composer studio software. The alternate procedure involved the use of the MATLAB® Audio System Toolbox™ to complete the same exercises. Each ability of the DSK board that was utilized had an analogue in the Audio System Toolbox™.

In the Texas Instruments’ C6713 DSK board and Code Composer setup, a student devises a block diagram model in the SIMULINK software accessed through MATLAB.® The model is then exported and subsequently uploaded to Code Composer. It is then uploaded to the DSK board via USB. Inputs and outputs are accessed through 3.5mm headphone jacks on the board. Standard inputs are audio files from the computer or from a microphone. Outputs are usually observed aurally through computer speakers or personal headphones—they can also be analyzed using an oscilloscope.

The Audio System Toolbox™ software in the lab had students conduct the same experiments, just without the intermediary hardware and instead utilized SIMULINK blocks directly to realize the real-time audio processes. The Audio System Toolbox™ in the laboratory exercises did not lead to a major shift in the actual completion of the tasks, but did change the in-lab workflow greatly. Instead of needing to save and re-export the model to Code Composer and upload to the DSK board, every time a modification was made, the student would run the model within SIMULINK itself. The Audio System Toolbox™ offered tools to take in real-time audio from the PC’s soundcard and output them to attached computer speakers or headphone jacks. The toolbox also featured a Spectrum Analyzer that replaced much of the functionality of the oscilloscope, although an audio output from the PC could be analyzed on the external oscilloscope as well to develop necessary technical skills for the curriculum.

**Assessment and Results**

**Statistical Analysis of Student Survey Results**

The laboratory assessment survey conducted in the Introduction to Signals & Systems course at the end of the semester asked students to consider several reflective questions. The complete
survey presented to students is show in Appendix A. The same survey was given to students who
used the DSK board in lab and those who used the MATLAB® Audio System Toolbox™. In
total, all 78 students in the Spring 2017 and Summer 2017 courses responded. Of these, 45 used
the DSK board for labs and 33 used the Audio System Toolbox™.

Several of these questions were pedagogical in nature and were posed to seek student impressions
of their self-learning after having completed the course and associated laboratories. The specific
questions relating to course learning, and hence pedagogical questions, are the first 8 questions in
the survey as show in Table 1 and Table 2. Of these, the first 4 questions were based on the
Accreditation Board of Engineering Technology (ABET) student learning outcomes, a.)–k.)
which are assessed for all core and design courses. Specifically, the first 4 questions in the student
survey encompass five key ABET learning outcome criteria:

a.) An ability to apply knowledge of mathematics, science, and engineering
b.) An ability to design and conduct experiments, as well as to analyze and interpret data
e.) An ability to identify, formulate, and solve engineering problems
i.) A recognition of the need for, and an ability to engage in life-long learning
k.) An ability to use the techniques, skills, and modern engineering tools necessary for
   engineering practice

Table 1. DSK board User Student Responses to Pedagogical Lab Survey Questions 1.–4.
   (complete survey in Appendix A)

<table>
<thead>
<tr>
<th>Question (DSK board users only)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>n</th>
<th>M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall, this laboratory contributed to my knowledge of the material</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>24</td>
<td>15</td>
<td>45</td>
<td>4.20</td>
<td>0.66</td>
</tr>
<tr>
<td>Overall, this laboratory increased my interest in the Signals and Systems</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>21</td>
<td>16</td>
<td>45</td>
<td>4.11</td>
<td>0.86</td>
</tr>
<tr>
<td>The skills and concepts taught in laboratory were well integrated with those in class</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>15</td>
<td>21</td>
<td>45</td>
<td>4.20</td>
<td>0.92</td>
</tr>
<tr>
<td>The laboratory helped me think critically about course material</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>21</td>
<td>18</td>
<td>45</td>
<td>4.27</td>
<td>0.69</td>
</tr>
<tr>
<td>The lab manuals were clear and easy to follow and implement</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>24</td>
<td>15</td>
<td>45</td>
<td>4.27</td>
<td>0.75</td>
</tr>
<tr>
<td>Time was effectively spent during lab</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>20</td>
<td>21</td>
<td>45</td>
<td>4.33</td>
<td>0.80</td>
</tr>
<tr>
<td>The TA aided in my understanding of the concepts in the laboratory exercises</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>33</td>
<td>45</td>
<td>4.71</td>
<td>0.51</td>
</tr>
<tr>
<td>The lab equipment and software effectively helped in understanding the concepts</td>
<td>0</td>
<td>4</td>
<td>9</td>
<td>18</td>
<td>14</td>
<td>45</td>
<td>3.93</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Statistical analyses of student survey results were completed for the two semesters in which the
MATLAB® Audio System Toolbox™ was used: Spring 2017 and Summer 2017. A one-tailed
Table 2. Audio System Toolbox™ User Student Responses to Pedagogical Lab Survey Questions 1.–4. (complete survey in Appendix A)

<table>
<thead>
<tr>
<th>Question (Audio System Toolbox™ users only)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>n</th>
<th>M</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, this laboratory contributed to my knowledge of the material</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>11</td>
<td>18</td>
<td>33</td>
<td>4.42</td>
<td>0.71</td>
</tr>
<tr>
<td>2. Overall, this laboratory increased my interest in the Signals and Systems</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>10</td>
<td>17</td>
<td>33</td>
<td>4.33</td>
<td>0.78</td>
</tr>
<tr>
<td>3. The skills and concepts taught in laboratory were well integrated with those in class</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>10</td>
<td>17</td>
<td>33</td>
<td>4.33</td>
<td>0.78</td>
</tr>
<tr>
<td>4. The laboratory helped me think critically about course material</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>14</td>
<td>17</td>
<td>33</td>
<td>4.45</td>
<td>0.62</td>
</tr>
<tr>
<td>5. The lab manuals were clear and easy to follow and implement</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>15</td>
<td>11</td>
<td>33</td>
<td>4.09</td>
<td>0.75</td>
</tr>
<tr>
<td>6. Time was effectively spent during lab</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>20</td>
<td>33</td>
<td>4.45</td>
<td>0.80</td>
</tr>
<tr>
<td>7. The TA aided in my understanding of the concepts in the laboratory exercises</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>29</td>
<td>33</td>
<td>4.85</td>
<td>0.51</td>
</tr>
<tr>
<td>8. The lab equipment and software effectively helped in understanding the concepts</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>14</td>
<td>16</td>
<td>33</td>
<td>4.36</td>
<td>0.94</td>
</tr>
</tbody>
</table>

t-test with a significance level of $\alpha = 0.1$ was performed for each of the questions on the survey. The survey employed a standard Likert scale that asked students to provide a numerical value between 1 = Strongly Disagree and 5 = Strong Agree. The null hypothesis used to run the test states that there is no difference in the mean responses between the group that used DSK boards and the group that used the Audio System Toolbox™. During the Summer of 2017, an accelerated form of the course was taught with one laboratory section that utilized only the Audio System Toolbox™. The student survey was administered again at the end of this section and the results were tabulated along with the original and are shown in Table 1. There were 11 additional students that took the course in the summer.

Overall, higher mean scores with tighter standard deviations for users who experienced the Audio System Toolbox™ in lab are noted. When statistical p-value analysis is completed comparing mean values for the DSK versus Audio System Toolbox™ platforms, at a significance level of $\alpha = 0.1$, there are two survey questions whose student response average values differ significantly when looking at just the results for Spring 2017:

- “The lab manuals were clear and easy to follow and implement” ($p = 0.0696$)
- “The lab equipment and software effectively helped in understanding the concepts” ($p = 0.0649$).

Upon further inspection, the data shows that the mean results were higher for students using the DSK boards for the former question and higher for students using the Audio System Toolbox for the latter question.
Table 3. P-values of T-tests to compare means between survey results of students using DSK boards versus the MATLAB® Audio System Toolbox.™ (α = 0.1 or less in bold)

<table>
<thead>
<tr>
<th>Question</th>
<th>Spring 2017</th>
<th>Spring + Summer 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overall, this laboratory contributed to my knowledge of this material</td>
<td>0.4595</td>
<td><strong>0.0775</strong></td>
</tr>
<tr>
<td>2. Overall, this laboratory increased my interest in Signals and Systems</td>
<td>0.3734</td>
<td>0.1219</td>
</tr>
<tr>
<td>3. The skills and concepts taught in laboratory were well integrated with those in class</td>
<td>0.3925</td>
<td>.2510</td>
</tr>
<tr>
<td>4. The laboratory helped me think critically about the course material</td>
<td>0.3810</td>
<td>0.1086</td>
</tr>
<tr>
<td>5. The lab manuals were clear and easy to follow and implement</td>
<td><strong>0.0696</strong></td>
<td>0.1625</td>
</tr>
<tr>
<td>6. Time was effectively spent during lab</td>
<td>0.3894</td>
<td>0.2543</td>
</tr>
<tr>
<td>7. The TA aided in my understanding of the concepts in the laboratory exercises</td>
<td>0.3229</td>
<td>0.1076</td>
</tr>
<tr>
<td>8. The lab equipment and software effectively helped in understanding the concepts</td>
<td><strong>0.0649</strong></td>
<td><strong>0.0162</strong></td>
</tr>
</tbody>
</table>

For the Spring and Summer 2017 combined results, there is a significant difference for the following two questions:

- “Overall, this laboratory contributed to my knowledge of this material” (p = 0.0775)
- “The lab equipment and software effectively helped in understanding the concepts” (p = 0.0162).

In both instances, the Audio System Toolbox™ software based approach had the higher mean. It should be noted that the last question posed regarding laboratory equipment and learning, question 8., has the most significant p-value difference between means when comparing the DSK to the Audio System Toolbox™ platform.

Qualitative Analyses of Student Feedback

Analysis of key words provided by students from the survey based on the question “What would you change about the laboratory section” appear as Word Clouds in Figs. 3 and 4. Other than the common words, “lab” and “labs” which appear in all student responses as well as the answer to the question, “What would you change,” being very commonly, “Nothing,” several more interesting trends appear.

Notable in the DSK responses is a student emphasis on “equipment,” “boards,” “work,” and of course, “DSK.” These common responses can be attributed to student statements regarding the need to troubleshoot and manage the hardware in ways that are not necessary using the software-based Audio System Toolbox.™
Figure 3. Word Cloud of student responses regarding the DSK board.

Figure 4. Word Cloud of student responses regarding the Audio System Toolbox.
The Audio System Toolbox™ feedback responses in Fig. 4, other than the above mentioned common words, emphasize the keywords “manual,” “use,” “less,” and “all.” These words seem to be a result of student comments regarding the laboratory manual instructions, ease of use of the Audio System Toolbox,™ and less time spent debugging hardware.

Comparison of Efficiencies in Time

Laboratory timing data for both the standard TI DSK board labs and those using the new MATLAB® Audio System Toolbox™ were collected from notes compiled by the laboratory teaching assistants after each exercise which was focused on potential improvements for future offerings. Major student difficulties and troubling concepts were noted. The average time it took to complete the exercise was also recorded. These values were combined with the times reported in a prior work where the same laboratory exercises were completed with the DSK boards as well as the Beagleboard-xM. Values are rounded to the nearest 15 minutes and are shown in Fig. 5.

Of the comments left by students as a result of the end-of-semester survey, it is worth more fully reading a few selected comments; these comments are summarized in Table 4. Of note amongst these student comments are the often encountered difficulty in use of the DSK board hardware or “equipment” as well as challenges with software implementation using the intermediary Code Composer program that interfaces with the DSK board.

Table 4. Selected Comments from Student Survey

<table>
<thead>
<tr>
<th>Selected Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Less use of DSK boards... they were often difficult to get to work properly.”</td>
</tr>
<tr>
<td>“I would make the instructions on how to use the Code composer software more clear.”</td>
</tr>
<tr>
<td>“Better equipment, as most of the equipment was faulty, and most of the time spent was troubleshooting physical equipment.”</td>
</tr>
</tbody>
</table>

Discussion of Real-Time Audio in the Lab

Efficiencies Realized: Hardware- versus Software-based Audio

With the implementation of the software-based workflow, many steps were removed. Originally, students had to develop a model in SIMULINK, export that model to Code Composer, and then upload to the DSK board, adding complexity, confusion, and more failure points when compared to the Audio System Toolbox.™ With the use of the Audio System Toolbox,™ students could input audio directly to the PC’s soundcard and see the results on the software’s Spectrum Analyzer. The built-in Spectrum Analyzer images produced by the Audio System Toolbox™ are not as robust as those found on a traditional standalone oscilloscope. Thus, it is not a perfect transition as it would be useful for students to see a clearer image to compare the amount of noise present and determine it’s source.
Figure 5. Average Time to Complete each Laboratory Exercise in the Lab.

(DSK 2014 refers to the TI DSK board reported in prior 2014 work, BBxM 2014 refers to the Beagleboard-xM platform also reported in prior 2014 work, DSK 2017 refers to the TI DSK board studied here, and AST 2017 refers to the Audio System Toolbox™ software studied here.)

In terms of efficiencies realized in reducing time in lab, Fig. 5 does not show any definitive answer to differences in times between the lab sections. There are multiple factors that need to be considered. Each section is begun with a teaching assistant introduction to the material. While the teaching assistants are presenting the same prepared material, the length of individual introductions may vary. In addition, the number of questions asked by students in lab differs widely. In this study the two sections that introduced the Audio System Toolbox™ were led by the most senior teaching assistants, so there may have been a greater focus on answering conceptual questions that arose and teaching material, leading to a longer runtime. The data suggest that the Audio System Toolbox™ does lead to shorter average times to complete lab assignments. Further improvements may arise in future semesters with experience and use of the software.

Educational Considerations: Student Perceptions

A major point of feedback from the survey at the end of the course was that many students were frustrated with the laboratory equipment. Most of the time, this was related to the use of the DSK boards. In a comparison of the word clouds in Figs. 3 and 4, it can be seen that there are many negative responses to the use of the DSK board because of the frustrating nature of troubleshooting it in lab. Some of this frustration may also have been artificially generated as a result of the availability of another alternative. Out of the 45 responses for the question “What
would you change about the laboratory section of ECE 280L [Introduction to Signals & Systems]?” from students who used the DSK boards, 15 comments specifically mentioned a desire to remove or alter the use of the boards because of technical difficulties that severely impacted the educational experience. There were also many concerns about a disconnect between the concepts taught in class and the concepts practiced through the exercises. The laboratory exercises were designed to provide supplemental context for concepts introduced in class and these connections may be difficult to discern when hardware issues take up a great amount of time during the lab period.

Returning to the quantitative survey results, it can be reasonably concluded that students preferred the Audio System Toolbox™. Any dissatisfaction with the lab manuals from the group using the Audio System Toolbox™ during Spring 2017 may be a result of it being the first semester it was used. Minor clarifying changes were made to the lab manual at the end of the Spring 2017 semester in response to these student concerns. Those changes seem to have been received favorably in the Summer 2017 term as noted by the reduction of differentiation when including that data in the mean p-value analysis (i.e. higher p-value is observed between Spring 2017 and Spring + Summer 2017 when comparing DSK and Audio System Toolbox™ means for question 5. “The lab manuals were clear and easy to follow and implement”).

Two further notes bear mention regarding the Summer 2017 offering of the course when the Audio System Toolbox™ was newly employed for laboratories. First, the summer session is a 6-week long experience where labs occurs twice a week, as opposed to the normal 14 week semester with labs occurring once a week. Hence, while covering the same content, the pace of the course is more accelerate during the summer. Second, the teaching assistant who aided students in the Summer 2017 session had experience when taking the course with the DSK board. However, the TA instructed the labs using the Audio System Toolbox™ for the first time. Training directly from the senior, experienced lab TAs was given beforehand to provide familiarity with the new software. Still, it should be noted that this was the TA’s first time instructing with the use of the Audio System Toolbox™ laboratories as well as being the TA’s first time assisting in the laboratory for this course. However, the data is still revealing of core metrics.

**Pedagogical Implications: Teaching Assistant Impressions**

Much of the impetus to experiment with alternative hardware for signal processing laboratories came internally from laboratory teaching assistants involved in the course. The identified need for change came as a result of time spent during laboratory sessions troubleshooting student hardware setups. With the DSK boards, physical defects could easily halt a student group, and often fixes dealt with loose or broken audio jacks and cables, or the processes used to interface with the board itself such as the use of Code Composer software. The teaching assistants expressed a desire to spend more time helping students gain an understanding of concepts in the laboratory rather than troubleshooting equipment.

At the same time, the teaching assistants noted that the Audio System Toolbox™ was not a perfect replacement for the DSK boards. There was a noticeable latency throughout the software system that did have an effect on the ability to discern major changes in audio outputs, important
in being able to understand the concepts being taught through the exercises. For example, in Lab 6: Voice Scrambler/Descrambler, the Audio System Toolbox\textsuperscript{TM} model that is used and developed inverts the incoming audio signal and cuts off any input above a frequency of 2 kHz. When the same input signal is fed through the DSK board and a PC with SIMULINK, the output is much less distorted. Also, it was noted that the software-based Spectrum Analyzer as part of the Audio System Toolbox\textsuperscript{TM} does not at present provide as clean a signal as the available bench-top oscilloscopes in lab (Keysight DSO-X 3012A 100 MHz Digital Storage Oscilloscope) with spectrum analyzer capability. As a work-around, outputs from the PC can be feed directly to an external oscilloscope. This practice actually has some pedagogical advantages as one of the goals of the core courses within the ECE curriculum is to familiarize students with hands-on test & measurement equipment such as the oscilloscope since such skills are necessary in practice and are used extensively in upper-level courses.

**Conclusions**

At Duke University we have replaced the traditional method of using a hardware-based solution for real-time audio processing in the introductory signal processing course with a software-based solution. Originally, the C6713 DSK board sold by Texas Instruments was used for laboratory exercises involving real-time signal processing. In this paper, this hardware-based solution has been replaced by the MATLAB\textsuperscript{R} Audio System Toolbox\textsuperscript{TM} which was recently released by The MathWorks, Inc. and packaged with MATLAB\textsuperscript{R} and SIMULINK. The toolbox offers sufficient functionality and is able to input and output audio through the PC’s soundcard. The motivation for the change in real-time signal processing was due in part to outdated supporting software compatibility (Code Composer Studio and Windows XP) as well as student and teaching assistant feedback about frustrations in troubleshooting hardware handshaking. The use of the Audio System Toolbox\textsuperscript{TM} is shown to have reduced the complexity of the lab exercises while still providing no change or improvement in learning outcomes as determined by end-of-semester student survey results. In this study, 78 student responses were collected with 45 coming from DSK board users in lab and 33 from Audio System Toolbox\textsuperscript{TM} users. The survey questions whose student response average values differ the most based on the platform at a significance values of $\alpha = 0.1$ include, “The lab manuals were clear and easy to follow and implement” ($p = 0.0696$), “The lab equipment and software effectively helped in understanding the concepts” ($p = 0.0649$), “Overall, this laboratory contributed to my knowledge of this material” ($p = 0.0775$), and “The lab equipment and software effectively helped in understanding the concepts” ($p = 0.0162$). In all instances, the Audio System Toolbox\textsuperscript{TM} software-based approach for real-time audio applications in the laboratory showed higher mean scores than the traditional hardware-based approach.

**Recommendations**

From the responses of students and teaching assistants, our recommendation is to consider replacing hardware used for real-time audio experiments with a software-based solution such as the Audio System Toolbox\textsuperscript{TM} in SIMULINK. In the past, an external board was necessary to
perform these experiments, but that is rapidly changing. This will allow for more efficient exercises in terms of time and physicality and a focus on the concepts that are being taught rather than troubleshooting the functionality of the components. An important caveat is that it is also beneficial for students to experience both hardware- and software-based solutions in order to understand the strengths and limitations of each as it applies to real-life applications, which is an important overarching outcome of the laboratory section. Thus, a potential framework would be to have the students develop and implement exercise models in software and have a teaching assistant have a hardware solution setup separately to compare results.

The following table provides the major pros of a hardware-based versus a software-based solution for real-time audio processing for laboratory experiments for a course in signals and systems.

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional method and thus has stronger existing infrastructure</td>
<td>Reduces complexity of setup</td>
</tr>
<tr>
<td>Less noise in output signal</td>
<td>Reduces time to complete exercises</td>
</tr>
<tr>
<td>True real-time signal output</td>
<td>Provides sufficiently clean signal</td>
</tr>
<tr>
<td>Multiple input and output ports</td>
<td>Easier for teaching assistants to troubleshoot</td>
</tr>
</tbody>
</table>

ability to purchase with MATLAB® license

Acknowledgements

The authors would like to thank the teaching assistants who contributed to this work in the Spring 2017 semester: Jocelyn Corey ’18, Vishnu Gottiparthy ’18, Alim Ladha ’18, Cristina Lai ’18, Suzhou Li ’18, and Sivaneshwaran Loganathan ’17. In particular, Siva Loganathan contributed richly to this work on par with that of the authors in terms of introducing, testing, and implementing the new MATLAB® Audio System Toolbox™ in the laboratory setting. In addition, special thanks goes to Dr. Michael Gustafson of Duke University who instructed the Introduction to Signals & Systems course in the Spring and Summer 2017 semesters when this study was conducted.
References


ECE 280L Lab Survey
* Required

1. **Overall, this laboratory contributed to my knowledge of the material** *
   *Mark only one oval.*

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

2. **Overall, this laboratory increased my interest in the Signals and Systems** *
   *Mark only one oval.*

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

3. **The skills and concepts taught in laboratory were well integrated with those in class** *
   *Mark only one oval.*

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

4. **The laboratory helped me think critically about course material** *
   *Mark only one oval.*

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

5. **The lab manuals were clear and easy to follow and implement** *
   *Mark only one oval.*

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

6. **Time was effectively spent during lab** *
   *Mark only one oval.*

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>
7. The TA aided in my understanding of the concepts in the laboratory exercises *

Mark only one oval.

[ ] 1  [ ] 2  [ ] 3  [ ] 4  [ ] 5

Strongly Disagree  [ ]  [ ]  [ ]  [ ]  [ ]  Strongly Agree

8. On average, about how many hours did you spend on lab reports or lab-related work per week (do not include homework or coursework hours outside of class): *

Mark only one oval.

[ ] 0-1 hrs.
[ ] 1-2 hrs.
[ ] 2-3 hrs.
[ ] 3-4 hrs.
[ ] 4-5 hrs.
[ ] 5-6 hrs.
[ ] 6-7 hrs.
[ ] 7-8 hrs.
[ ] 8+ hrs.

9. Did you use the Audio System Toolbox or the DSK boards? *

Mark only one oval.

[ ] Audio System Toolbox
[ ] DSK Boards

10. The lab equipment and software effectively helped in understanding the concepts *

Mark only one oval.

[ ] 1  [ ] 2  [ ] 3  [ ] 4  [ ] 5

Strongly Disagree  [ ]  [ ]  [ ]  [ ]  [ ]  Strongly Agree

11. Which Lab Exercise did you have the most trouble with? *

Check all that apply.

[ ] Lab 1: Music Synthesis
[ ] Lab 2: Intro to Simulink
[ ] Lab 3: Digital Audio Effects
[ ] Lab 4: DTMF Dialer
[ ] Lab 5: Sampling and Aliasing
[ ] Lab 6: Scrambler/Descrambler
[ ] Lab 7: AM Radio
12. Which lab exercise did you think was the most effective and why? *

13. Which concept in any of the labs did you have the most trouble with and why? *

14. Which helped the most in understanding the lab material? *
   Check all that apply.
   
   [ ] Lectures
   [ ] Background of Lab Manual
   [ ] Explanations provided by the TA
   [ ] Discussion Questions in the Lab Manual
   [ ] Other: ____________________________

15. What would you change about the laboratory section of ECE 280L? *