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Upgrading Digital Signal Processing Development Boards in an Introductory Undergraduate Signals and Systems Course

Mr. Kip D. Coonley, Duke University

Kip D. Coonley received the M.S. degree in Electrical Engineering from Dartmouth College, Hanover, NH, in 1999 and the B.S. degree in Physics from Bates College, Lewiston, ME, in 1997. Following graduation from Dartmouth, he developed electronically controlled dimmers for fluorescent and incandescent lamps at Lutron Electronics, Coopersburg, PA. From 2001 to 2005, he was a Research Engineer at RTI International, where he designed high-efficiency thermoelectrics using epitaxially grown superlattice thin-film structures. Since 2005, he has been the Undergraduate Laboratory Manager in the Department of Electrical and Computer Engineering at Duke University, Durham, NC. His interests include undergraduate engineering education, RFID, power electronics, plasma physics, and thin films.

Mr. Justin Miles, Duke University

Justin Miles received the M.S. (2013) and B.S. (2008) degrees in Electrical Engineering from North Carolina State University. He has been a Research and Development engineer in the Department of Electrical and Computer Engineering since 2008. Justin's primary responsibility is managing laboratory equipment and components for the undergraduate labs. Justin also provides support in the development of new lab exercises and integration of new equipment and components in all of the undergraduate laboratories.

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Abstract

This paper presents the results of a controlled one semester study where students responded to a hardware upgrade from the Texas Instruments TMS320C6713 DSK development board to the Beagleboard-xM platform in the laboratory associated with the first Electrical and Computer Engineering course in signal processing at the undergraduate level. The sophomore-level course in signal processing 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. In this study, both the TMS320C6713 DSK development board with its 225MHz processor and the newer Beagleboard-xM with its 1 GHz processer provide students with a real-time, programmable signal-processing hardware platform that enhances the learning experience. The DSK board requires the use of an intermediary software tool, Code Composer Studio to compile and program whereas the Beagleboard interfaces directly with MATLAB. Analysis of the usefulness of the hardware upgrade was carried out by assessing students' acceptance of the DSK versus the Beagleboard-xM in terms of its usefulness and usability over four key laboratory experiments: Digital Audio Effects, Touch-Tone Phone, Voice Scrambler-Descrambler, and Sampling and Aliasing. The extent to which the two hardware platforms were able to successfully achieve learning outcomes in the course is also presented.

Introduction

Real-time signal processing as part of an introductory signal processing course complements in-class lectures by using project-centric and industry hardware. It also introduces students to tools that they will be able to use in senior design courses and after graduation. The best choice of hardware platform needs to emphasize concepts related to signal processing by offering a relevant, real-world design experience.[1] Hardware-based Digital Signal Processing (DSP) laboratories have had marked success in providing hands-on, realistic lab experiences to undergraduate students in an Electrical and Computer Engineering (ECE) curriculum.[1,2,3] 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.[2]

The course studied here is typically taken by sophomore or junior level students in both the ECE and Biomedical Engineering (BME) fields. In it, MATLAB 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 were 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. In the Fall 2014 semester when the Beagleboard-xM hardware platform was introduced in the laboratory, 65 undergraduate students were enrolled in the course. There were six laboratory sections each week. For the four laboratories involving the use of a DSP hardware platform, a pair of students in each lab section was asked to perform the current laboratory using the new Beagleboard-xM while the remaining groups used the existing C6713 DSK platform. The pair using the Beagleboard changed for each laboratory and the most any single pair used the Beagleboard was two labs. Ultimately, 35 students—just over 50% of the class—experienced using the Beagleboard as a DSP hardware platform in the laboratory.

Four laboratories in the course implemented the use of DSP hardware: Real-Time Digital Audio Effects, Dual-Tone Multi-Frequency Touch Tone Phone, Sampling and Aliasing, and Voice Scrambler-Descrambler. In the Real-Time Digital Audio Effects laboratory, sampling rate, difference equation representation, and block diagram implementation in SIMULINK are used when students manipulate audio signals so that they can see and hear the effect of various algorithms. In the Dual-Tone Multi-Frequency Touch Tone Phone laboratory, correlation is applied through telephony with pure sinusoidal signals which translate into numbers on an LED "keypad" or display. In the Sampling and Aliasing laboratory, speech coding and decoding based on a fixed sampling rate illustrates the Nyquist criterion. The Voice Scrambler-Descrambler laboratory uses the principles of modulation and demodulation with speech or music and includes anti-aliasing filter design.[2] Prior to the course being offered with both the Beagleboard-xM and C6713 DSK hardware, the laboratory exercises were updated and re-tested, respectively including instructions and example images to make them compatible with either platform and provide an equivalent lab experience.

Real-Time Signal Processing Hardware Selection

The motivation to pursue a new platform for the DSP laboratories in an undergraduate digital signal processing course stems from the desire to eliminate outdated Texas Instruments Code Composer Studio v3.3 software. Code Composer v3.3 provides the link between the signal processing platform and MATLAB's SIMULINK toolbox. Communication between Code Composer Studio v3.3 and SIMULINK had been handled automatically when a SIMULINK model was built. However, subsequent versions of Code Composer removed this seamless communication link and have therefore been avoided in the course to prevent students from needing to learn how to use this new software tool in addition to SIMULINK.

One goal in the selection of signal processing hardware was to choose a platform that would expose students to a single board computer early on in the curriculum. Single board computers were targeted in the selection process due to their increasing popularity. The Beagleboard-xM, Raspberry Pi, and Arduino platforms were all investigated. Each includes a Target Support Package for SIMULINK. The Raspberry Pi does not offer a native audio input jack or on-board DSP capability which makes real-time signal processing—a vital part of the signals and systems laboratory exercises—challenging. The Arduino lacks audio capability, processor speed, and size for the necessary DSP computations. The Beagleboard-xM has the advantage of including built-in audio jacks and a dedicated on-board signal processing integrated circuit block. It has been used in comparable teaching laboratories.[5] A comparison of hardware specifications between the existing TMS320C6713 DSK development board and the Beagleboard-xM is shown in Table I. For compatibility with Code Composer software, the lab currently uses the Windows XP operating system. Unlike the current C6713 DSK board, the Beagleboard is compatible with the Windows 7 operating system. Since Windows XP is no longer supported by the Microsoft Corporation as of April 8, 2014, transitioning to Windows 7 is vital to maintaining network security in the lab.[4]

Table I. Summary of Hardware platform capabilities

	TMS320C6713 (current lab platform)	**Beagleboard-XM** (investigated lab platform)
Flash	512KB	4GB
RAM	512MB SD	512MB LPDDR
Processor Speed	225MHz	1GHz
Instructions/Second	1800 MIPS	2000+ MIPS
Video	Yes	Yes
OS	Windows XP (CCS v3.3 not compatible with Windows 7)	Windows (or any OS capable of running MATLAB)
Peripheral Software	MATLAB Target Support Package and CCS	MATLAB Target Support Package
Programming Cable	USB	Serial to USB
DSP	C6713	C64+TMDSP core
Price	$395/kit	$200/board
		
Links	http://www.ti.com/tool/tmdsdsk6713	http://beagleboard.org/Products/BeagleBoard-xM

The Beagleboard-xM was chosen based on its software requirements, hardware interface options, direct compatibility with SIMULINK without the need for intermediary Code Composer software, ability to operate using the latest Windows operating system, and lower cost than any of the other options investigated. The Beagleboard-xM is a programmable board designed utilizing the Linux operating system. It has been used by researchers and hobbyists alike and has revolutionized the accessibility of complete programmable hardware systems to end-users. In addition, with its faster processor—1GHz for the Beagleboard versus 225MHz for the currently used C6713 DSK board—the Beagleboard carries the potential for expanding laboratory experiments to include emerging areas of research including video and image processing.

Assessment & Results

Student Survey

Undergraduate students enrolled in the sophomore-level signals and systems course were asked to provide anonymous feedback at the end of the semester on their lab experience using the

Beagleboard-xM platform as compared to the existing TMS320C6713 DSK development board. To randomize user selection and reduce bias, a different group was given the Beagleboard-xM for each of the four laboratories. The DSK board was used for all other signal processing hardware-based laboratories. The survey questions employed a standard five-level Likert scale ranging from "Strongly Disagree"(1) to "Strongly Agree"(5). In the survey, five categorical areas were queried: Usability, Usefulness, Acceptance, Relationship to Accreditation Board of Engineering Technology (ABET) student outcomes, and Relationship to Course Objectives. Table II show the questions, number of responses, mean value for each question, and standard deviations. One question, Question #2 in the Usability category is phrased in the negative, "TA assistance was required in setting up the Beagleboard-xM for use in this laboratory." For this question, a "better" result is for students to choose "Strongly Disagree." This question is analyzed separately as a metric of student aid required to complete the laboratory exercises with the new hardware platform. Also, a question was repeated in the survey—Questions #1 and #2 in the Relationship to Course Objectives category—and serves to indicate the degree to which student responses are repeatable. Since student responses at any given time are dependent upon so many uncontrolled factors, differences in responses to this question motivate grouping questions of the same kind together for more reliable analysis. In addition, terms used in the Usability category such as "smooth" and "adequate" may be interpreted differently. Any uncertainty in student interpretation of questions can also be mitigated by aggregating response data into categories for analysis. Lastly, also within the Usability category, one question ask students to assess how "flexible" the Beagleboard-xM seemed. This question was posed to understand how versatile the new Beagleboard-xM appeared to students after one or two lab experiences with it as compared to the existing DSK board which they used for all other DSP hardware-based laboratories.

Figure 1 shows the results of aggregate responses within a category. Mean values and standard deviations for each have been calculated. Since more than one response is being compared, a measure of independence of results can be deteremined. Cronbach's Alpha (α) reliability coefficient indicates non-randomness of data when values of $\alpha > 0.70$. Pearson p-values based on a Chi-squared variance test have also been determined. The p-value is a measure of the statistical significance compared to the null-hypothesis—in this case no difference, or the "Neither Agree nor Disagree" response. P-values where $p < 0.05$ indicate significance and that the null-hypothesis can be rejected.

A general analysis of these results suggests that the new Beagleboard-xM DSP hardware platform was well received. Taken as a whole, 1/3 of the students "Strongly Agree" or "Agree" to the survey questions; 1/2 indicate no change, "Neither Agree nor Disagree;" and only about 1/8 "Disagree" or "Strongly Disagree." At a minimum, it can be safely concluded that students did not strongly object to the use of the new hardware. In fact, if anything, the Beagleboard was better from most students' perspectives than the existing TI C6713 DSK hardware.

Table II. Student Assessment for Signal Processing Hardware Exercises

Category	Questions	1	2	3	4	5	N	M	SD
1=Strongly Disagree 2=Disagree 3=Neither Agree Nor Disagree 4=Agree 5=Strongly Agree									
Usability	1. Setting up the simulation parameters for the Beagleboard-xM was straightforward.	0	6	17	9	3	35	3.26	0.85
	2. TA assistance was required in setting up the Beagleboard-xM for use in this laboratory.*	0	2	12	12	9	35	3.80	0.90
	3. The Beagleboard-xM itself was a useable and adequate platform to complete this laboratory.	1	2	11	17	3	34	3.56	0.86
	4. The interface between the Beagleboard-xM hardware and SIMULINK software was smooth and adequate during the course of this laboratory experiment.	0	6	15	9	4	34	3.32	0.91
	5. In general, the Beagleboard-xM was a more flexible platform to work with than the DSK board used in other labs.	1	5	18	8	2	34	3.15	0.86
	6. Overall, the functionality of the Beagleboard-xM was satisfactory, considering that this was its first implementation in ECE 280L labs.	0	0	15	16	3	34	3.66	0.65
Usefulness	1.The Beagleboard-xM helped me to understand the concepts presented in this laboratory.	0	2	17	14	1	34	3.41	0.66
	2.In general, the Beagleboard-xM motivated me to learn more about the course subject matter of Signals & Systems.	0	5	20	8	1	34	3.15	0.70
	3.In comparison with the DSK board used in other lab exercises, the Beagleboard-xM provided for more advanced applications.	0	4	19	9	2	34	3.26	0.75
Acceptance	1.I enjoyed using the Beagleboard-xM for this laboratory in ECE 280L.	0	8	22	3	1	34	2.91	0.67
	2.Laboratory exercises using the Beagleboard-xM compliment the course with a useful, hands-on tool for the exploration of Signals & Systems.	0	1	16	15	2	34	3.53	0.66
	3.I would consider using the Beagleboard-xM in labs outside of this course if such an opportunity were to arise.	1	7	16	8	2	34	3.09	0.9
	4.I would recommend the Beagleboard-xM to other students as a useful signal processing platform.	0	6	19	9	1	35	3.14	0.73
	5. I would recommend that the Beagleboard-xM be used moving forward in place of the DSK board as the laboratory signal processing platform in ECE 280L.	4	2	18	8	2	34	3.06	1.01
ABET Student Outcomes	1. The use of the Beagleboard-xM contributed to my ability to apply knowledge of mathematics, science, and engineering.	0	4	19	10	1	34	3.24	0.70
	2. Using the Beagleboard-xM in this course contributed to my ability to identify, formulate, and solve engineering problems.	0	1	22	9	2	34	3.35	0.65
	3. I would say that the Beagleboard-xM allowed me to use techniques, skills, and modern engineering tools necessary for engineering practice.	0	1	17	15	1	34	3.47	0.61
Relationship to Course Learning Objectives	1. The use of the Beagleboard-xM in this laboratory contributed to my basic foundation in the mathematical modeling and analysis of continuous-time and discrete-time signals.**	0	1	15	14	3	33	3.58	0.71

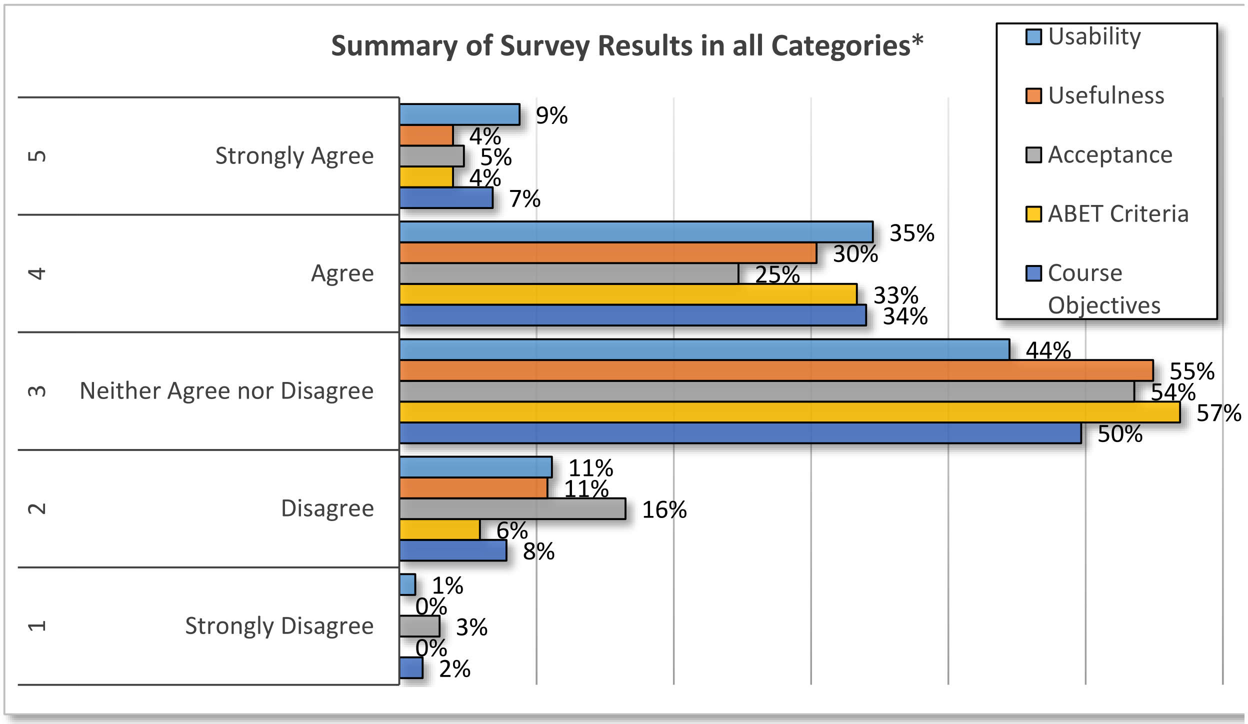
	2. The use of the Beagleboard-xM in this laboratory contributed to my basic foundation in the mathematical modeling and analysis of continuous-time and discrete-time systems.**	0	2	14	14	3	33	3.55	0.75
	3. The use of the Beagleboard-xM in this laboratory contributed to my understanding of fundamental signal and system properties.	0	0	19	11	2	32	3.47	0.62
	4. The use of the Beagleboard-xM in this laboratory contributed to my understanding of how signals and systems can be approximated using orthogonal basis functions.	3	6	16	6	1	32	2.88	0.94
	5. The use of the Beagleboard-xM in this laboratory contributed to my understanding of the Fourier and Laplace transforms.	1	5	19	6	1	32	3.03	0.78
	6. The use of the Beagleboard-xM in this laboratory contributed to my understanding of the relationship between continuous time and discrete time.	1	4	16	10	2	33	3.24	0.87
	7. The use of the Beagleboard-xM in this laboratory contributed to my basic foundation of applications of linear time-invariant systems.	0	5	14	12	2	33	3.33	0.82
	8. The use of the Beagleboard-xM in this laboratory contributed to my appreciation of how MATLAB can be used for exploring signals and systems.	0	0	17	12	4	33	3.61	0.70
	9. The use of the Beagleboard-xM in this laboratory contributed to my understanding of the programming and operation of digital signal processing hardware.	0	0	16	15	2	33	3.58	0.61

** Usability, Question #2 phrased in the negative*

*** Question repeated and provides statistical comparison*

In the survey area of "Usability,"—with Question #2 regarding TA assistance removed—the mean Likert scale score is M = 3.39, just above the average value of 3, with a SD = 0.83. Cronbach's Alpha reliability coefficient of 0.7696 indicates that results are above the 0.7 cutoff and are thus not randomly distributed, although they do have a wide spread as indicated by the large SD value. The Pearson p-value of 0.2525 is less than the 0.5 cutoff which indicates that the null-hypothesis, "Neither Agree nor Disagree", can be rejected—in other words, the Beagleboard-xM is more useable according to those surveyed than the DSK board for the labs evaluated. Percentages of students responding to the Usability questions indicate that almost half, 44% "Strongly Agree" or "Agree" that the Beagleboard-xM was a highly useable platform. Another 44% felt that it was just as good by responding, "Neither Agree nor Disagree." A much smaller 12% perceived the Beagleboard-xM to be less than highly useable.

In the survey area of "Usefulness," the mean Likert scale score is M = 3.27 with a SD = 0.70. The alpha value of 0.2910 is well below the 0.7 cutoff and indicates that for this small data set (only 3 questions), it cannot be stated whether the data are or are not randomly distributed from one another. The p-value of 0.6736 is very high and therefore does not allow the rejection of the null-hypothesis—"Neither Agree nor Disagree"—in regards to the overall usefulness of the Beagleboard-xM platform. Percentages of students responding to the Usefulness questions indicated that a third, 34% "Strongly Agree" or "Agree" that the Beagleboard-xM was a highly useable platform while the majority, 55% felt that it was just as good. Only 11% perceived the Beagleboard-xM to be less than useful when surveyed at the end of the semester.



Category	Questions	N	M	SD	□	p-value
Usability*	5	34	3.39	0.83	0.7696	0.2525
Usefulness	3	34	3.27	0.70	0.2910	0.6736
Acceptance	5	34	3.14	0.86	0.6828	0.0138
ABET Criteria	3	34	3.35	0.65	0.7603	0.4256
Course Objectives	9	33	3.36	0.76	0.9277	0.0430

** data excludes Usability, Question #2, "TA Assistance was required…"(for results refer to Figure 5)*

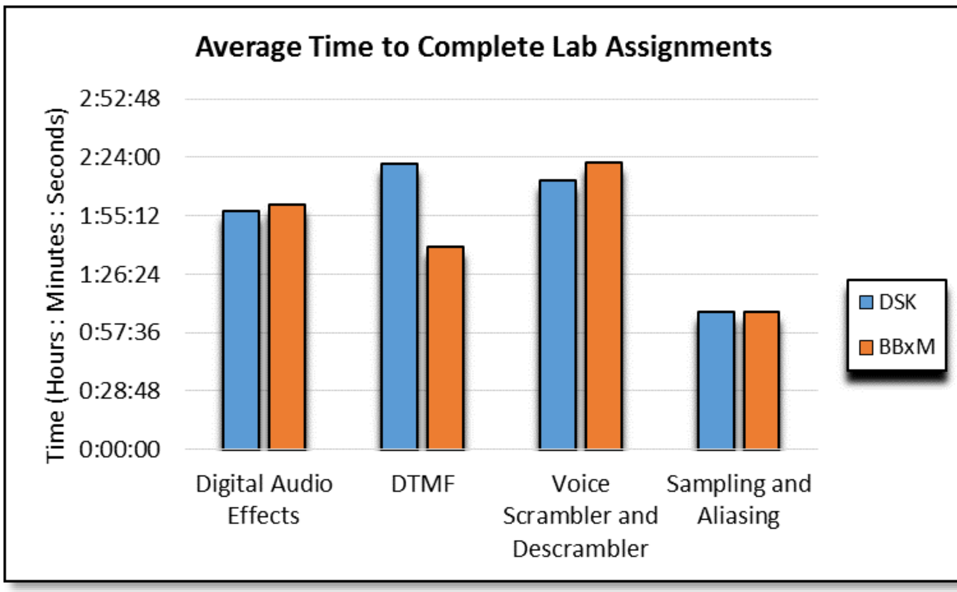
Figure 1. Summarized Survey Results for Signal Processing Hardware Exercises

In the survey area of "Acceptance," the mean Likert scale score is M = 3.14 with a SD = 0.86. The alpha reliability coefficient of 0.6828 indicates that question responses are most likely not randomly distributed, although they do have a wide spread. And the p-value of 0.0138 indicates that the Beagleboard-xM might be a better accepted platform than its TI DSK counterpart. Across the five Acceptance questions, 30% of students indicated that the Beagleboard-xM was much more or more accepted than the DSK board, while 54% felt that it was as good or the same, and 19% perceived the Beagleboard-xM to be less acceptable than the DSK board.

In questions about the "Relationship to Accreditation Board of Engineering Technology (ABET) Student Outcomes," the mean Likert scale score is M = 3.35 with a SD = 0.65. The alpha reliability coefficient of 0.7603 indicates that even this small set of data (3 questions) is not random. The p-value of 0.4256 is quite large and thus does not allow the rejection of the null-hypothesis—namely, there was no change in relation to ABET criteria as a result of introducing the Beagleboard-xM in these signal processing laboratories. Of the students responding, 37%

indicated that the Beagleboard-xM met or exceeded meeting ABET criteria, 57% were neutral, and only 6% felt that it fell short of meeting ABET criteria.

Finally, in terms of the Beagleboard-xM's "Relationship to Course Objectives," the mean Likert scale score is M =3.36 with a SD = 0.76. This category received the highest alpha score of 0.9277 indicating that the data are highly reliable. This category also received the lowest p-value of 0.0430 which indicates that student responses differ significantly from the average "3" value, or that the platform does relate very well to course objectives. Percentage of student responses show that 41% "Strongly Agree" or "Agree" that the Beagleboard-xM met course objectives; half, 50% "Neither Agree" nor "Disagree" that it did so; and 10% felt that it did not do a good job of meeting course objectives. It should be noted that the questions in this section are phrased specifically toward the use of the Beagleboard as it relates to course learning objectives.



DSP hardware platform	Total time (all 4 labs)
Beagleboard-xM	7 hrs, 9 min, and 58 sec
TMS320C6713 DSK	7 hrs, 38 min, and 16 sec
Δ difference	*28 min, 18 sec (6.6 %)*

Figure 2. Average Time to Complete Signal Processing Hardware Exercises

Time to Complete Laboratories & Assistance Needed

Laboratory teaching assistants (TAs) introducing and managing the labs were asked to provide timing feedback for all student groups in their laboratory section. The results of the measured time to complete the four laboratories in which a signal processing hardware platform was used are shown in Figure 2. The overall time to complete the laboratories using the Beagleboard-xM was slightly faster by 28 minutes or 6.6% than when the same experiments were completed using the TI DSK platform. Interestingly, this time reduction favoring the Beagleboard is due primarily to the much shorter amount of time needed to complete the second DSP hardware-based laboratory.

For the second DSP hardware laboratory—Dual-Tone Multi-Frequency Touch Tone Phone—the average completion time using the Beagleboard was greatly reduced—by nearly 40 minutes. This surprising observation is likely a result of the fact that for this lab, some of the groups who completed the first lab, Digital Audio Effects using the Beagleboard also completed this second lab with the same hardware. For most of the laboratories involving DSP hardware—Digital Audio Effects, Voice Scrambler-Descrambler, and Sampling and Aliasing—the time to complete the lab experiment using the TI DSK board is nearly the same as that with the Beagleboard-xM. It should be noted that whereas the TI C6713 DSK board was used several times by students for these labs and thus familiarity with it increased with each use, this was not generally the case for the Beagleboard. These results, then, suggest that even a one-time exposure to the Beagleboard increases familiarity with the hardware enough to overcome its learning curve and thus accelerate the lab experience. It is likely that the labs can be completed even more quickly using the Beagleboard as familiarity with it increases. Even more encouraging is the fact that the lab groups who used the Beagleboard for the first DSP lab requested to continue using it for the next lab experience; they were only dissuaded from doing so for subsequent laboratories as they were explicitly instructed to use the DSK platform instead for the sake of the hardware experiment at hand. Overall, these observations indicate great promise in adopting the Beagleboard as the DSP hardware platform of choice for future DSP laboratories.

Student responses to Usability, Question #2 regarding TA assistance, are shown in Figure 3. Predictably, students required initial help when implementing this new hardware platform for the first time: a little over 1/2 felt that TA assistance was needed while 1/3 were neutral and very few, only about 1/16 did not feel that TA assistance was needed in setting-up the Beagleboard hardware for labs. Since student responses were collected after only one, and at most two labs using the Beagleboard, it is very likely that the need for TA assistance in setting-up this platform for use would decrease with increased exposure to the hardware.

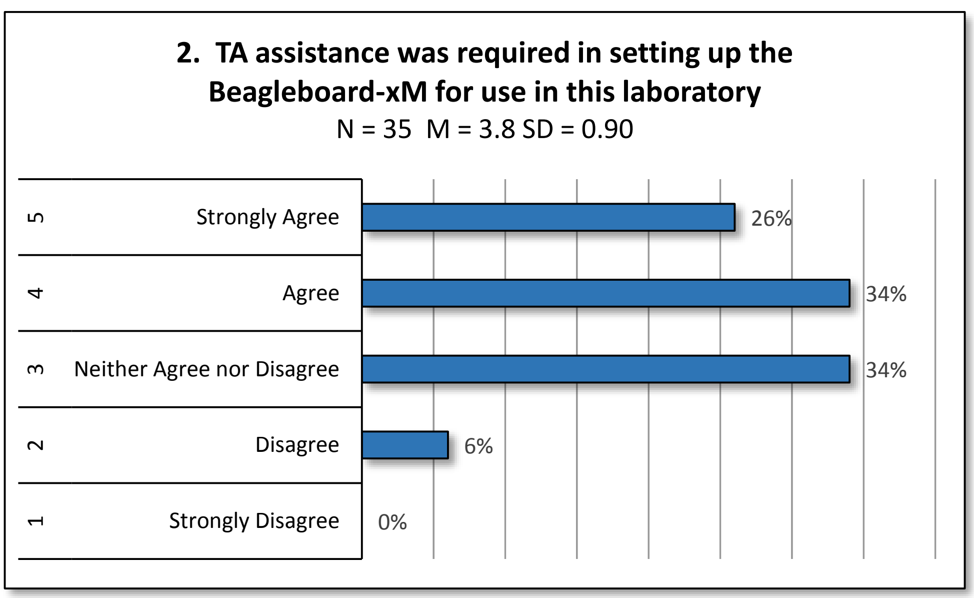


Figure 3. Student responses to Question #2 regarding Teaching Assistant Assistance

Student and Teaching Assistant Comments and Feedback

Lastly, students and laboratory TAs were asked for their feedback in separate surveys soliciting their impressions regarding the four DSP laboratories using either the Beagleboard-xM or the DSK platform. A keyword summary of these comments is collected in Table III.

Table III. Summary of student and Teaching Assistant Feedback using DSP hardware

	… for TMS320C6713 DSK	**… for Beagleboard-xM**
Student survey response keywords….	more TA help available just as easy to use less set up time more stable	ease of use worked effectively connects directly to MATLAB/SIMULINK longer program upload time little TA experience with hardware
Teaching Assistant feedback form keywords…	faster upload time handshaking between software an issue causes MATLAB errors required intermediary, Code Composer software	smoother process interfaces directly with MATLAB/SIMULINK took less time (overall) less error-prone (i.e. MATLAB did not need to be restarted)

In general, the Beagleboard-xM performed well, but suffered from longer program upload times and lack of teaching assistant experience—not surprising considering this was the first time the hardware had been used in the course. The TI DSK board was more familiar to teaching assistants. However, it suffered from software interfacing issues ("handshaking") and from a laboratory consistency point of view, required dedicated computers running outdated Windows XP software. Overall, there were distinct advantages to using the Beagleboard whose implementation and download speeds should only improve with pedagogical experience in the laboratory and with improvements in computational efficiency.

Conclusions

In this comparative study of the Beagleboard-xM and the TMS320C6713 DSK hardware platform for use in the first ECE course in signal processing at the undergraduate level, results indicate that the Beagleboard-xM is very suitable for exploring concepts central to signal processing. Students who used the Beagleboard-xM for at least one of the four DSP labs found it to be better or at least just as good as the current TMS320C6713 DSK platform in the following assessment areas: Usability (88%), Usefulness (89%), Acceptance (84%), Relationship to Accreditation Board of Engineering Technology (ABET) Student Outcomes (94%), and Relationship to Course Objectives (91%). In addition, despite the slower upload speed of the Beagleboard-xM, the total amount of time required to complete DSP hardware-based laboratories using the Beagleboard-xM was reduced by 6.6%. Further, and perhaps most encouraging, is that results suggest even a one-time lab experience with the Beagleboard is enough to overcome any learning curve it might have and thus accelerate lab completion. Finally, comments and feedback solicited from students and teaching assistants reflect positively on the Beagleboard-xM. In general, the results of this study suggest great promise for adopting the Beagleboard-xM as the DSP hardware platform of choice for future DSP laboratories.

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