SIMULATION OR REAL-TIME?

Cameron H. G. Wright

Dept. of Elec. and Comp. Engineering
University of Wyoming, WY, USA
c.h.g.wright@ieee.org

Thad B. Welch

Dept. of Elec. and Comp. Engineering
Boise State University, ID, USA
t.b.welch@ieee.org

Michael G. Morrow

Dept. of Elec. and Comp. Engineering
University of Wisconsin, WI, USA
morrow@ieee.org

ABSTRACT

After many years of practicing, reading and writing about signal processing education, we have observed some common themes. This paper discusses the trade-off of simulation versus the use of real-time processing on real-world signals as a motivator for signal processing students. A real-time DSP demonstration accompanies the presentation of this paper.

Index Terms— signal processing education, demonstration, simulation, real-time

1. INTRODUCTION

The authors have been highly involved in signal processing education for over 20 years. Over that time, we have written many papers (at ICASSP, ASEE, and other venues) that have described our various lessons learned, projects that worked well, and described many tools that we made freely available to educators [1–26]. In all of those years, our fundamental goal of maximizing student engagement has not changed.

We believe that if students are truly interested in a topic, not only will they pursue course knowledge, but they will regularly exceed our educational expectations. This belief has been confirmed over and over with our students at multiple institutions.

Most professors agree that interactive learning, exercises, and demonstrations are invaluable for helping students understand a given concept [22, 27–36]. We've come to believe that even more effective than demonstrations where students sit passively are actual hands-on exercises and projects [2, 3, 9, 10, 15, 17, 23]. We even provide a book and website that supports hands-on projects [37, 38].

In our opinion, the *hook* that metaphorically *reels* the students in is working with real-world signals, preferably on real-world hardware. This is what industry does, and a significant number of our students will go on to work for industry.

2. WHAT PLATFORM?

The question immediately arises: what hardware platform should be used? The hardware target of choice can vary and will naturally evolve as technology continues to advance. We've seen the transition from mainframe offline computing, to specialized processor architectures that led to the first DSP chips, to floating-point processors, to field programmable gate arrays (FPGAs), to high performance computing (HPC) or multicore signal processors, the reinvigoration of the hobby or maker movement with low-cost boards such as Arduino and Raspberry Pi, to power hungry, massively parallel, graphical processing units (GPUs), and even to implementing signal processing algorithms on smartphones. This list is by no means complete, and even if we cataloged all of the major advances, in the next year or the next decade, something new and probably revolutionary will surely be added to the list.

This constant advancement is what keeps industry going, and we believe it also keeps a great number of engineers employed and students applying for admission to our Colleges of Engineering.

Years ago, with the widespread adoption of personal computers into our classrooms and teaching labs, simulation took over and most students were amazed by the presentations that could be provided. We believe that those days are gone; they are probably at least a decade in the past and today's students are not at all enthralled with simulation. The only possible exception to this is if the simulation involves a video, but today's students are at best simply tolerant of these "canned" simulation presentations. However, hands-on demonstrations with real-world signals still excite most students.

Working with real-world signals in an interactive, hands-on manner implies real-time DSP. While real-time DSP can be performed using low-cost boards such as Arduino [39–41] or Raspberry Pi, [42–44] we also find that real-world hardware adds to the efficacy of the demonstration. By real-world hardware, we mean hardware (and the associated development tools) that may very well be used to develop a commercial product when the student becomes a working engineer. This tends to make Arduino and Raspberry Pi and similar solutions less attractive.

The authors have used many platforms over the years, with the majority being based on one of the commercial-level DSP chips from Texas Instruments (the TMS320x chips). We have used C31, C6201, C6211, C6711, C6713,... most recently, we have been using the OMAP-L138, which incorporates both a C6748 DSP core and an ARM-9 core. The Texas Instruments hardware is programmed with the professional-grade Code Composer Studio, which the students seem to appreciate. There are certainly other hardware and software options, but this is what we have been using.

3. HANDS-ON DEMONSTRATIONS

The possibilities are many for hands-on demonstrations using real-world signals and real-time DSP hardware. For example, we have engaged our students in hands-on real-time demonstrations that include

- sampling and quantization;
- digital filter design, implementation, and testing;
- unstable system implementation;
- phase response and group delay;
- modulation and demodulation;
- beam forming, using inexpensive microphones;
- biomedical signal conditioning;
- encoding and decoding Caller-ID signals;
- control of high-amperage external devices;
- sampling rate conversion;

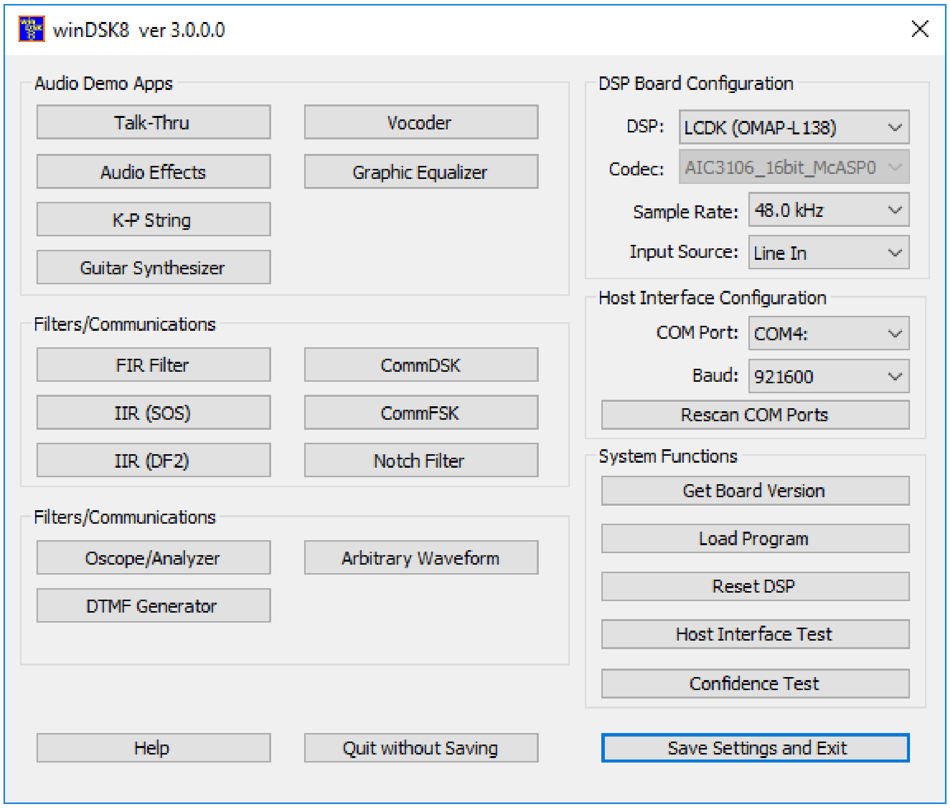

Fig. 1: The main winDSK8 user interface.

- signal processing of financial data;
- software defined radio;
- adaptive filters;
- video signal manipulation;
- multispectral imaging;
- and the basics of optical engineering.

The possibilities are endless.

No one realistically expects every ECE or EE professor to become expert in the hardware and software tools for real-time DSP, but that isn't necessary to be able to incorporate such demonstrations into their courses. The authors have routinely provided tools, freely available to educators, that make it relatively simple to get students involved with real-time hands-on demonstrations. For example, the winDSK tool, and it's follow-ons winDSK6 and now winDSK8, exist to allow any professor to perform real-time demonstrations with little effort [4, 13, 19].

The latest version, winDSK8, can work with the OMAP-L138 multicore system-on-a-chip, or with the single core C6713. The main user interface for winDSK8 is shown in Fig. 1.

4. RESULTS

Some discussion of the results of a few of the more recent demonstration topics listed above may be helpful to professors seeking to incorporate real-time hands-on demonstrations into their courses.

At ICASSP 2013, we discussed using adaptive filters as the demonstration vehicle for our students' real-time hands-on exercises [21]. We found that the majority of our students agreed with our belief that the adaptive filter demonstration helped them understand the underlying signal processing concepts, despite the fact that only one class period was spent on this topic. A survey question designed to assess the efficacy of DSP demonstrations in general averaged a score of 4.29 on a 5-point Likert scale, where 5 is most effective. This certainly is in line with our anecdotal experiences regarding the teaching effectiveness of demonstrations in the classroom.

At ICASSP 2014, we described how we used a video see-through application to help students understand not only signal processing concepts, but also the basics of video signal formatting [22]. Using real-time digital signal processing rather than the more comfortable method of using off-line processing (such as using MATLAB) greatly increased the effectiveness of the exercise. While "see-through" is a simple process on the surface, we find that students must establish confidence in the hardware and software platform before any significant learning can begin. In the audio realm, a talk-through project accomplishes this. For moving on to a more complicated signal such as video, we used a see-through project.

This point deserves more discussion, as many professors consider it a waste of time. Including a bare-bones first project, such as talk-through or see-through, to build student confidence in the real-time platform is a valuable pedagogical approach. We have found that skipping this step greatly reduces student motivation to pursue the real cause of incorrect results from a real-time DSP exercise. That is, students are otherwise quick to "blame" the platform. Establishing a working baseline in the students mind, using talk-through or see-through, is definitely worth the time.

At ICASSP 2016, we discussed how signal processing can be used as a segue into related topics, such as optical engineering [24]. The daunting challenge of teaching practical optical engineering in a single course can be greatly reduced by taking advantage of existing student knowledge of signal processing concepts. In general, for students learning a new topic area, a particularly efficient and effective method takes best advantage of the students' prior knowledge. By making links to their existing cognitive frameworks, our students were far less intimidated by the new subject material, and more quickly mastered an acceptable level of expertise, compared to a "starting from scratch" approach to a new topic area.

At ICASSP 2018, we discussed how the new generation of affordable infrared (IR) cameras can be used for an interesting exercise in DSP for the students, in particular for introducing the concept of a multispectral signal [26]. These cameras provide both IR and visible images, hence the multispectral aspect. We described the use of a FLIR E60 IR camera in a graduate digital image processing course, in which both IR and visible images were used as the basis for an open-ended final project in the course that required them to design and implement an image fusion algorithm. By using both pre- and post-project questionnaires, we were able to confirm that the project was a positive experience for the students, and helped motivate them to master the course material.

5. CONCLUSIONS

Today there is a global need for engineers who are literate, confident, and competent in DSP. An obvious solution for supplying this need is for universities to educate new engineers. To help educate the next generation of DSP engineers, several powerful and highly versatile options are available. Real-time or quasi real-time systems can be implemented using, for example, microprocessors, field programmable gate arrays, dedicated DSP hardware, general-purpose processors, graphical processing units, or smart phones. We discussed our efforts above in using a number of different dedicated DSP hardware devices to enhance our students understanding of signal processing concepts and to develop a hardware and software skillset routinely sought by future employers. We also laid out the case that real-time, hands-on exercises or demonstrations, using real-world signals, is still one of the most motivating methods to use with today's students.

We strongly encourage faculty who teach DSP to incorporate demonstrations and hands-on experience with real-time hardware for their students. We have made various resources widely available to help in this endeavor, and they are freely available to educators.

6. REFERENCES

[1] C. H. G. Wright and T. B. Welch, "Teaching DSP concepts using MATLAB and the TMS320C31 DSK," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 6, pp. 3573–3576, Mar. 1999.

[2] C. H. G. Wright and T. B. Welch, "Teaching real-world DSP using MATLAB," *ASEE Comput. Educ. J.*, pp. 1–5, January–March 1999.

[3] T. B. Welch, M. G. Morrow, and C. H. G. Wright, "Teaching practical hands-on DSP with MATLAB and the C31 DSK," in *Proceedings of the 2000 ASEE Annual Conference*, June 2000. Paper 1320-03.

[4] M. G. Morrow and T. B. Welch, "winDSK: A windows-based DSP demonstration and debugging program," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 6, pp. 3510–3513, June 2000. (invited).

[5] M. G. Morrow, T. B. Welch, C. H. G. Wright, and G. W. P. York, "Demonstration platform for real-time beamforming," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 5, pp. 2693–2696, May 2001.

[6] C. H. G. Wright, T. B. Welch, D. M. Etter, and M. G. Morrow, "A systematic model for teaching DSP," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. IV, pp. 4140–4143, May 2002. Paper 3243.

[7] C. H. G. Wright, T. B. Welch, D. M. Etter, and M. G. Morrow, "Teaching hardware-based DSP: Theory to practice," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 4, pp. 4148–4151, May 2002.

[8] K. E. Wage, J. R. Buck, T. B. Welch, and C. H. G. Wright, "The continuous time signals and systems concept inventory," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. IV, pp. 4112–4115, IEEE, May 2002. Paper 2985.

[9] C. H. G. Wright, T. B. Welch, D. M. Etter, and M. G. Morrow, "Teaching DSP: Bridging the gap from theory to real-time hardware," *ASEE Comput. Educ. J.*, pp. 14–26, July–September 2003.

[10] T. B. Welch, R. W. Ives, M. G. Morrow, and C. H. G. Wright, "Using DSP hardware to teach modem design and analysis techniques," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. III, pp. 769–772, Apr. 2003.

[11] T. B. Welch, M. G. Morrow, and C. H. G. Wright, "Using DSP hardware to control your world," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. V, pp. 1041–1044, May 2004. Paper 1146.

[12] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Caller ID: An opportunity to teach DSP-based demodulation," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. V, pp. 569–572, Mar. 2005. Paper 2887.

[13] M. G. Morrow, T. B. Welch, and C. H. G. Wright, "A host port interface board to enhance the TMS320C6713 DSK," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. II, pp. 969–972, May 2006.

[14] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Teaching rate conversion using hardware-based DSP," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. III, pp. 717–720, Apr. 2007.

[15] C. H. G. Wright, M. G. Morrow, M. C. Allie, and T. B. Welch, "Using real-time DSP to enhance student retention and engineering outreach efforts," *ASEE Comput. Educ. J.*, pp. 64–73, October–December 2008.

[16] C. H. G. Wright, M. G. Morrow, M. C. Allie, and T. B. Welch, "Enhancing engineering education and outreach using real-time DSP," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. III, Apr. 2008.

[17] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "The DSP of money," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2309–2312, Apr. 2009.

[18] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Software defined radio: inexpensive hardware and software tools," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2934–2937, Mar. 2010.

[19] M. G. Morrow, C. H. G. Wright, and T. B. Welch, "winDSK8: A user interface for the OMAP-L138 DSP board," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2884–2887, May 2011.

[20] T. B. Welch, M. G. Morrow, and C. H. G. Wright, "Connexions and the SPEN fellows program," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2785–2788, Mar. 2012. paper 3664.

[21] M. G. Morrow, C. H. G. Wright, and T. B. Welch, "Real-time DSP for adaptive filters: A teaching opportunity," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, May 2013.

[22] A. Rothenbuhler, C. H. G. Wright, T. B. Welch, and M. G. Morrow, "DSP see-through: Going beyond talk-through," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2247–2251, May 2014.

[23] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Leveraging student knowledge of DSP for optical engineering," in *Proceedings of the 2015 IEEE Signal Processing and Signal Processing Education Workshop*, pp. 148–153, Aug. 2015.

[24] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Signal processing concepts help teach optical engineering," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 6275–6279, Mar. 2016.

[25] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Reinforcing signal processing theory using real-time hardware," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 6329–6333, Mar. 2017.

[26] C. H. G. Wright and T. B. Welch, "Image fusion: an introduction to multispectral signal processing," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 7001–7005, Mar. 2018. Paper: SS-L16.3.

[27] C. S. Burrus, "Teaching filter design using MATLAB," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 20–30, Apr. 1993.

[28] R. F. Kubichek, "Using MATLAB in a speech and signal processing class," in *Proceedings of the 1994 ASEE Annual Conference*, pp. 1207–1210, June 1994.

[29] R. G. Jacquot, J. C. Hamann, J. W. Pierre, and R. F. Kubichek, "Teaching digital filter design using symbolic and numeric features of MATLAB," *ASEE Comput. Educ. J.*, pp. 8–11, January–March 1997.

[30] J. H. McClellan, C. S. Burrus, A. V. Oppenheim, T. W. Parks, R. W. Schafer, and S. W. Schuessler, *Computer-Based Exercises for Signal Processing Using* MATLAB 5. MATLAB Curriculum Series, Upper Saddle River, NJ (USA): Prentice Hall, 1998.

[31] J. W. Pierre, R. F. Kubichek, and J. C. Hamann, "Reinforcing the understanding of signal processing concepts using audio exercises," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 6, pp. 3577–3580, Mar. 1999.

[32] W.-S. Gan, Y.-K. Chong, W. Gong, and W.-T. Tan, "Rapid prototyping system for teaching real-time digital signal processing," *IEEE Trans. Educ.*, vol. 43, no. 1, pp. 19–24, 2000.

[33] T. S. Hall and D. V. Anderson, "A framework for teaching real-time digital signal processing with field-programmable gate arrays," *IEEE Trans. Educ.*, vol. 48, no. 3, pp. pp. 551–558, 2005.

[34] A. Spanias, K. Huang, R. Ferzli, H. Kwon, V. Atti, V. Berisha, L. Iasemides, H. Krishnamoorthi, M. B. S. Misra, K. Tsakalis, and S. Haag, "Interfacing Java-DSP with a TI DSK board," *ASEE Comput. Educ. J.*, vol. XVII, Jul.–Sep. 2007.

[35] H. Kwon, V. Berisha, A. Spanias, and V. Atti, "Experiments with sensor motes and Java-DSP," *IEEE Trans. Educ.*, vol. 52, no. 2, pp. 257–262, 2009.

[36] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Using student knowledge of linear systems theory to facilitate the learning of optical engineering," in *Proceedings of the 2015 ASEE Annual Conference*, pp. 26.1683.1–26.1683.11, June 2015. DOI: 10.18260/p.25019.

[37] T. B. Welch, C. H. G. Wright, and M. G. Morrow, *Real-Time Digital Signal Processing: From MATLAB to C with C6x DSPs*. Boca Raton, FL (USA): CRC Press, 3rd ed., 2017.

[38] "RT-DSP website." `http://www.rt-dsp.com`.

[39] W. J. Esposito, F. A. Mujica, D. G. Garcia, and G. T. Kovacs, "The Lab-In-A-Box project: An Arduino compatible signals and electronics teaching system," in *Proceedings of the 2015 IEEE Signal Processing and Signal Processing Education Workshop (SP/SPE)*, pp. 301–306, Aug. 2015. doi: 10.1109/DSP-SPE.2015.7369570.

[40] M. A. Wickert, "Real-time DSP basics using Arduino and the Analog Shield SAR codec board," in *Proceedings of the 2015 IEEE Signal Processing and Signal Processing Education Workshop (SP/SPE)*, pp. 59–64, Aug. 2015. doi: 10.1109/DSP-SPE.2015.7369528.

[41] J. Jaldén, X. C. Moreno, and I. Skog, "Using the Arduino Due for teaching digital signal processing," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 6468–6472, 2018. doi: 10.1109/ICASSP.2018.8461781.

[42] M. S. Pattichis, S. Celedon-Pattichis, and C. Lopez-Leiva, "Teaching image and video processing using middle-school mathematics and the Raspberry Pi," in *Proceesings of the IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 6349–6353, Mar. 2017. doi: 10.1109/ICASSP.2017.7953378.

[43] J. Marot and S. Bourennane, "Raspberry Pi for image processing education," in *Proceedings of the 25th European Signal Processing Conference (EUSIPCO)*, Aug. 2017. doi: 10.23919/EUSIPCO.2017.8081633.

[44] M. Azarpour, J. Siska, and G. Enzner, "Realtime binaural speech enhancement demo on Raspberry Pi," in *Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 6572–6573, Mar. 2017. doi: 10.1109/ICASSP.2017.8005296.