REINFORCING SIGNAL PROCESSING THEORY USING REAL-TIME HARDWARE

Cameron H. G. Wright
Dept. of Elec. and Comp. Engineering
University of Wyoming, WY
c.h.g.wright@ieee.org

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

Michael G. Morrow
Dept. of Elec. and Comp. Engineering
University of Wisconsin-Madison, WI
morrow@ieee.org

ABSTRACT

Today there is a global need for engineers who are "DSP literate." An obvious solution for supplying this need is to educate the next generation of DSP engineers. To do this, several powerful and highly versatile options are available. Real-time or quasi-real-time systems can be implemented using, for example, microprocessors, FPGAs, dedicated DSP hardware, general-purpose processors, graphical processing units, or smartphones. This paper discusses our efforts over the years using various dedicated DSP hardware devices to enhance our student's understanding of signal processing concepts and to develop the hardware and software skill-set routinely sought by future employers. Specifically, we introduce version three of winDSK8, a Windows-based graphical program that can control any one of three different Texas Instrument (TI) floating-point, real-time, DSP boards.

This paper was invited for the special session, "Advances in Signal Processing Education." A real-time DSP demonstration will be part of our presentation.

Index Terms— signal processing, signal processing education, real-time, DSP hardware

1. INTRODUCTION

An analysis of the content of the papers presented at the education sessions during the past five ICASSP conferences was conducted. The education session papers were categorized based on a variety of metrics, but for this paper, the most important finding dealt with the use or discussion of hardware systems. For this discussion, hardware is defined as a circuit board, camera, microprocessor, real-time DSP board, etc. This is to distinguish actual hardware from virtual hardware, its model, or a simulation. Table 1 summarizes these findings.

Despite the dramatic decrease in education session papers over the past five years, the percentage of papers involving hardware systems remains above 50%. This anecdotally reinforces what the authors have believed for decades: that in-class demonstrations and/or student hands-on experience with real hardware systems is highly motivational, reinforces classroom lectures/discussions, and provides students with a required skill for almost any engineer or engineering student who is aspiring toward gainful employment with a company that actually sells a hardware-based product.

It is also worth noting that during this five-year period, the utilization of smartphones, tablets, graphical processing units (GPUs), and low-cost microprocessors to teach and perform DSP theory and/or its applications has increased tremendously.

Some of these trends are based on availability, with (for example) almost 100% market penetration of smartphones among U.S. college students. Others are based upon simple economics, with an entry-level lab system based on a general purpose microprocessor, microcontroller, or system-on-chip (e.g., Raspberry Pi or Arduino) typically costing an order of magnitude less than an entry-level standalone real-time DSP hardware system (such as an OMAP-L138 LCDK from Texas Instruments). With regard to signal processing computations, the performance difference between these two hardware strategies is profound, but the hardware selection decision is often based almost entirely upon one of two factors:

1. the desire for the student to be able to purchase their own system for home use, or
2. affordability, if the university will purchase and provide the hardware to the students.

It should come as no surprise to educators that in these situations, availability and affordability, as opposed to hardware suitability, tend to drive a significant number of teaching decisions.

For example, we have noted an increasing number of papers presented at engineering education conferences in recent years where very inexpensive, general-purpose processor-based solutions (such as Arduino or Raspberry Pi) have been used to teach some basic DSP concepts. While these efforts require very little financial investment, using platforms that were originally intended for the hobbyist market, rather than using professional-grade DSP processors and development tools (as we have advocated for many years), puts a significant limitation on the kinds of programs that can be run in real-time, and doesn't provide the student with important "industry-grade" experience. In particular, we believe that only by exposing the students to standalone real-time DSP hardware systems will the students acquire the deep

Table 1: A partial result of the analysis of the technical content of the papers presented at the education sessions during the past five ICASSP conferences.

Year	ICASSP Location	Education Papers	Involving Hardware	Hardware-related papers
2012	Kyoto, Japan	12	6	50%
2013	Vancouver, BC, CA	5	4	80%
2014	Florence, Italy	4	2	50%
2015	Brisbane, AU	3	2	67%
2016	Shanghai, P.R.C.	3	2	67%

understanding of signal processing concepts and develop the hardware and software skill-set that is routinely sought by future employers.

In support of this teaching philosophy for DSP, we have developed, published, and continue to support a number of hands-on tools and teaching techniques to develop and enhance these highly desirable industry skills [1–36]. One of the central tools to this collection of work that we have made freely available to educators is the series of programs called by various names over the years: winDSK, winDSK6, and winDSK8. Our latest offering is a significant upgrade to the original program, winDSK.

2. OUR SOLUTION: THE WINDSK SERIES

As noted above, the winDSK series of programs changed names slightly over they years, primarily to reflect a change in the real-time DSP hardware that the program would support.

The winDSK8 program is the latest in the winDSK family of Windows-based software, which interfaces to Texas Instruments (TI) floating-point, real-time DSP boards. The original program, winDSK, supported the TI C31 DSK (DSP starter kit). Its eventual successor, winDSK6, supported a variety of TI C67xx DSKs. The latest iteration, winDSK8, supports both the C6713-based DSK and OMAP-L138-based DSKs. The OMAP-L138 is a multi-core processor from TI, containing both an ARM-9 general-purpose processor core and a C6748 floating-point DSP core; when connected to an OMAP-L138 DSP board, winDSK8 utilizes both cores. The OMAP-L138 boards supported by winDSK8 include the Zoom Experimenter Kit (from Logic PD, Inc.) and TI's fairly recent LCDK (Low Cost Development Kit). An example of the new winDSK8 graphical user interface is shown in Figure 1.

Code Composer Studio (CCS) is the integrated development environment (IDE) for a number of TI real-time DSP processors/boards, including those supported by winDSK8. During recent CCS updates, the latest C compiler included with the IDE no longer provided support for the COFF (Common Object File Format) files that had been used for many years to load a DSP program into the real-time hardware. Instead, the complier now only supports the newer ELF (Executable and Linkable Format) files for loading DSP programs into the real-time hardware. Version three of winDSK8 added the ability to load ELF files, in addition to maintaining support for the existing COFF loader.

The winDSK8 program can be used in a wide variety of courses for a number of purposes. For example, in a Microprocessor course, the following is a list of some of the demonstrations that are possible.

- Sampling and the effect of changing the effective sample frequency.
- Sampling and the effect of changing the signal quantization (varying from 16 bits-per-sample to 1 bit-per-sample).

These same demonstrations would be also be appropriate for a Signals and Systems course, along with the added winDSK8 demonstrations shown below.

- Spectral estimation, to include the analysis of periodic signals (Fourier series, Fourier transforms).
- Dual-tone multiple-frequency (DTMF) signaling.
- System impulse response and its practical implications.
- The ramifications and trade-offs of FIR versus IIR digital filtering.
- Implementation of digital filters to produce various audio affects.

In a DSP course, these same demonstrations would also be appropriate, but winDSK8 provides additional germane demonstrations shown below.

- Effects of ADC saturation and other distortions.
- Various digital filter implementation structures such as second-order sections (SOS) and direct form II (DF-II).
- Implementation and trade-offs of both FIR and IIR Notch filters.
- Time-frequency analysis of signals using dynamic spectrograms and waterfall displays.

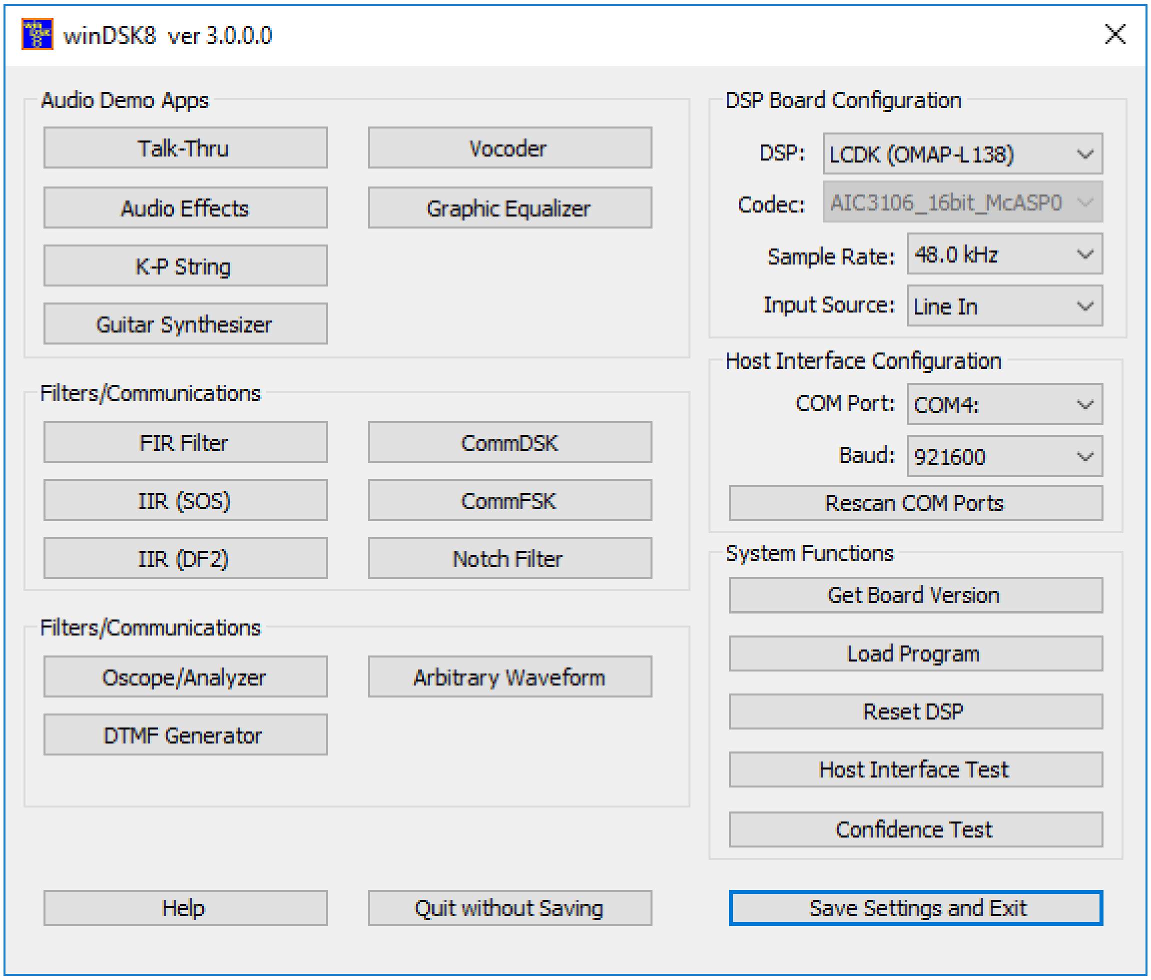

Fig. 1: The main opening screen of the the graphical user interface for the latest version of winDSK8.

In a Communications Systems course, additional demonstrations using winDSK8 could include the following.

- Frequency shift key (FSK).
- Digital communications signal generation and analysis of various data rates associated with
  - BPSK.
  - QPSK.
  - 8-QAM.
  - 16-QAM.
- Effects of pulse shaping, filtered versus unfiltered outputs, and performance with and without a variety of channel impairments for a variety of modulation schemes.

Finally, winDSK8 can also be used to improve motivation and insight in a real-time DSP course, and to get students to think more deeply about the type of real-time program that they want to create and implement. In our experience, few engineering students see a winDSK8 demonstration and walk away completely satisfied. Most of them are then inspired to change, try to improve, or design their own version of one of the demonstrations.

3. CONCLUSIONS

Microprocessors, FPGAs, dedicated DSP hardware, general-purpose processors, graphical processing units, tablets, and/or smartphones can all be used to enhance DSP education. While we have chosen to emphasize the use of dedicated DSP hardware, we firmly believe that there is no single best solution for exposing students to implementing DSP algorithms using real hardware devices.

As the available real-time DSP hardware has evolved, the winDSK family of programs has also evolved along with it, supporting the C31, the C6211, the C6711, the C6713, the OMAP-L138 (Zoom Experimenter kit), and now the OMAP-L138 LCDK. Each of these migrations to new hardware has required a unique communication system/interface to allow for high-speed host control of the real-time target. We note that winDSK8 marks the first use of a multi-core real-time target for this type of educational tool, as it uses two cores in its operation. The combination of winDSK8 and the OMAP-L138 in the LCDK has only recently become available, so no detailed assessment of classroom use yet exists. However, the authors hope this paper will alert educators to the pedagogical potential that could be realized with these new tools. All the latest software is also provided with the upcoming new edition of our real-time DSP textbook [37].

The winDSK8 program and all of the other software packages that we have developed are freely available for educational, non-profit use, and we invite user suggestions for improvement. Interested parties are also invited to contact the authors via e-mail.

4. 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] 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).

[4] M. G. Morrow, T. B. Welch, and C. H. G. Wright, "An inexpensive software tool for teaching real-time DSP," in *Proceedings of the 1st IEEE DSP in Education Workshop*, IEEE Signal Processing Society, Oct. 2000.

[5] M. G. Morrow, T. B. Welch, C. H. G. Wright, and G. York, "Teaching real-time beamforming with the C6211 DSK and MATLAB," in *Proceedings of the 2000 Texas Instruments DSP Educators and Third-Party Conference*, Aug. 2000.

[6] 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.

[7] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Poles and zeroes and MATLAB, oh my!," *ASEE Comput. Educ. J.*, pp. 70–72, April–June 2000.

[8] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "Teaching transfer functions with MATLAB and real-time DSP," in *Proceedings of the 2001 ASEE Annual Conference*, June 2001. Session 1320.

[9] 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.

[10] 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.

[11] M. G. Morrow, T. B. Welch, and C. H. G. Wright, "A tool for real-time DSP demonstration and experimentation," in *Proceedings of the 10th IEEE Digital Signal Processing Workshop*, Oct. 2002. Paper 4.8.

[12] T. B. Welch, D. M. Etter, C. H. G. Wright, M. G. Morrow, and G. J. Twohig, "Experiencing DSP hardware prior to a DSP course," in *Proceedings of the 10th IEEE Digital Signal Processing Workshop*, Oct. 2002. Paper 8.5.

[13] G. W. P. York, C. H. G. Wright, M. G. Morrow, and T. B. Welch, "Teaching real-time sonar with the C6711 DSK and MATLAB," *ASEE Comput. Educ. J.*, pp. 79–87, July–September 2002.

[14] 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.

[15] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "An inexpensive method to teach hands-on digital communications," in *Proceedings of the IEEE/ASEE Frontiers in Education Annual Conference*, pp. F2E19–F2E24, Nov. 2003.

[16] 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.

[17] 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.

[18] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Experiences in offering a DSP-based communication laboratory," in *Proceedings of the 11th IEEE Digital Signal Processing Workshop and the 3rd IEEE Signal Processing Education Workshop*, Aug. 2004.

[19] M. G. Morrow, T. B. Welch, and C. H. G. Wright, "Opening new doors: Enhanced educational opportunities with the TMS320C6713 DSK," in *Proceedings of the 2005 Texas Instruments Developer Conference*, Feb. 2005. Invited paper.

[20] 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.

[21] 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.

[22] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "CommFSK: A hardware approach to teaching FSK," in *Proceedings of the 12th IEEE Digital Signal Processing Workshop*, pp. 460–465, Sept. 2006.

[23] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Caller ID: A project to reinforce an understanding of DSP-based demodulation," *ASEE Comput. Educ. J.*, pp. 2–7, October–December 2006.

[24] C. H. G. Wright, T. B. Welch, M. G. Morrow, and G. Vineyard, "A hardware approach to teaching FSK," in *Proceedings of the 2007 ASEE Annual Conference*, June 2007.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] M. G. Morrow, C. H. G. Wright, and T. B. Welch, "WinDSK8: the continuing saga of winDSK," in *Proceedings of the 14th IEEE Digital Signal Processing Workshop*, Jan. 2011.

[31] 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.

[32] 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, 2nd ed., 2012.

[33] 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.

[34] C. H. G. Wright, M. G. Morrow, and T. B. Welch, "Comparison of DSP boards for classroom use," in *Proceedings of the 15th IEEE Digital Signal Processing Workshop*, Aug. 2013.

[35] 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.

[36] 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.

[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. Currently in press; available early 2017.