Theory, Invention, and Practice

The phrase "theory and practice gap" is well known, and you have probably heard this expression many times. Control and systems research is often inclined to theoretical studies, and our (theoretical) community has often been criticized for being "too theoretical" and not relevant to "*real* applications."

Of course, this viewpoint is overly simplistic, and such arguments can be refuted based on the immense number of applications that we have produced in our history. After all, *who could argue that Kalman filtering is irrelevant to reality?* Numerous fruitful and concrete examples are provided in the "Impact of Control Technology" [1]. Many more examples can be found in *IEEE Transactions of Control Systems Technology*.

Still, there is a disturbing element in the phrase "theory and practice gap." On one hand, theoreticians like to develop theories for their own sake. They would like to view their problems in a universal, effective, and clear perspective and strive to solve the problems in a general and far-reaching context. On the other hand, such a process is inevitably inclined toward abstraction, which often makes it difficult for the resulting theories to be readily appreciated by practitioners.

Digital Object Identifier 10.1109/MCS.2013.2258743
Date of publication: 12 July 2013

Nonetheless, we may feel the need that the theory we have developed is actually applied and indeed works in reality. After all, we are engineers, theoretical or not, and the ultimate goal of engineering is to contribute to the welfare of our society.

In this column, I would like to write about my own experience on theory, invention, and practice, including how I became more interested in applications and how that realization materialized. I would like to share some thoughts on what I did right and perhaps more on what I should have done but did not. I hope my two cents can help some readers to become more interested in inventions and get an idea of what we can do and how we can proceed from a tiny bit of a small idea.

(From left) Jay Farrell, Steve Yurkovich, Yutaka Yamamoto, and John Baillieul at a breakfast table in the Renaissance Austin Hotel, during the February 2013 IEEE meeting series.

AN INVENTION

Let's start with a little bit of background. I was studying sampled-data control theory from 1989 to the early 1990s. The crucial problem was that sampled-data systems contain two distinct time sets: continuous and discrete. The plant works in continuous time while the controller operates in discrete time. To make a long story short, the advances of sampled-data control theory in the early 1990s have made it possible to design a *discrete-time controller that makes the continuous-time performance optimal*.

This study led me to consider whether there was a close connection between sampled-data control theory and digital signal processing. In digital signal processing, there is also this dual nature of continuous- and discrete-time sets. At that time, the compact disc format was well established, and there was a technique called *oversampling DA converters*. To understand this technique, suppose digital data $f(1h)$, $f(2h)$, …, have been collected with sampling period h. Compact discs have $h = 1/44100$ s. Since digital data do not produce a sound, a hold device needs to be introduced. By that time, it was also recognized that it is better to subsample (i.e., oversample) the given sampling period to allow for a smoother interpolation, as shown in Figure 1. This idea was often justified by quoting the sampling theorem [2], which considers the reconstruction of an analog signal with as low of frequencies as possible from sampled data.

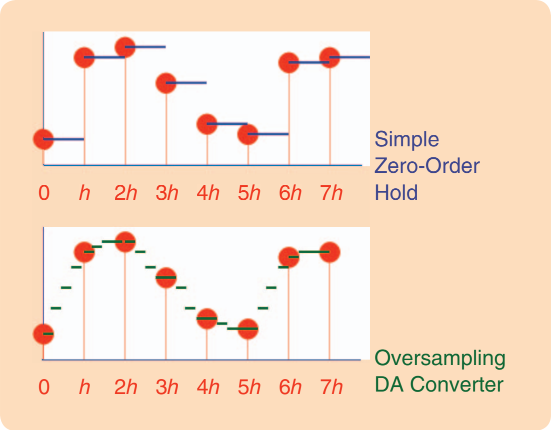

FIGURE 1 The contrast between standard zero-order hold and oversampling DA conversion.

I happened to be an audiophile and had read about such arguments several times by then but was left unconvinced. If you follow the paradigm by Shannon [2], you have to discard the high-frequency components beyond the Nyquist frequency, but it appeared to be a waste to oversample so much and still throw away all those high-frequency components.

It was then I came to realize a connection with sampled-data H-infinity theory. Consider a low-pass filter $F(s)$ that acts on a exogenous signal w to produce a target analog signal y that gets sampled, to become a sampled signal $y(nh)$, $n = 1, 2, \ldots$. A sampled-data H-infinity optimization problem can be formulated by a) upsampling (oversampling) $y(nh)$ to allow for intersampling interpolation and b) designing a discrete-time filter $K(z)$ that minimizes the overall error between the reconstructed signal v and delayed $y(t - mh)$, against all L^2 inputs w. This procedure may sound complicated, but it is actually quite straightforward once someone knows how to do sampled-data H-infinity design. I will not go into the full technical details here, which can be found in [3], but let me just add that the crucial difference here is that the anti-aliasing filter $F(s)$ is not an ideal low-pass filter, unlike in the Shannon paradigm.

MOVING ON

The result was remarkable. The resulting filter yielded a response with virtually no ringing effect, as seen in the Gibbs phenomenon normally observed with the conventional "linear phase" filters employed in CD processing (see Figures 2 and 3). I was encouraged by the result and tried to convince various manufacturers to produce a DA converter based on this new theory.

The outcome was disappointing. Most people were very conservative and either were not interested in trying a new idea or else not ready to listen at all. Some said it would be yet another tone controller. One person asked, "what did our competitors say?" In short, no one was eager to improve upon what they were doing in their day-to-day activities. Some were clearly worried about making mistakes. Some people were incredulous. Some were just sticking to what they had learned from their old textbooks.

In retrospect, their responses were largely my mistake also. I was naïve enough to think that everyone in industry would be very eager to have an advantage over their competitors and that they would all strive to explore new opportunities. I mean nothing derogatory. I had forgotten a very basic principle. We are all human, and everyone is afraid to try anything new when the outcome is uncertain. To make things worse, my only demo was virtual, processed only in a personal computer, with no real-time processing. It was probably expecting too much to ask them to imagine how the signal improvements that could be achieved with a new method.

As a side note, there was one exception. A venture capitalist in Tokyo became interested in my new theory, and we had worked together for two or three years. Unfortunately, there was a critical error in implementing the algorithm in fixed-precision arithmetic, and the method did not work as well on an actual circuit board as in emulations. I learned a precious lesson: always check the details step by step for yourself. No excuse can save a failure.

A TURNAROUND

A little while later, I was contacted by the Sanyo Electric Corporation. They saw my Web page and were interested in image processing using my filter. Skipping some of the details, we started working together on

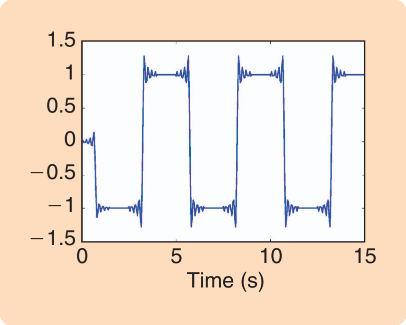

FIGURE 2 Time response of a conventional DA converter against a rectangular wave, showing much ringing due to the Gibbs phenomenon.

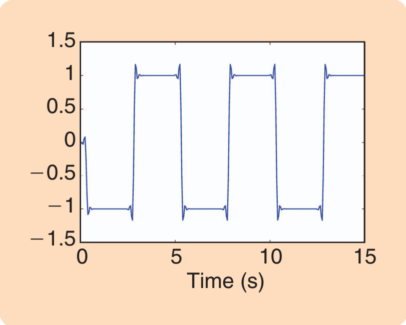

FIGURE 3 The response of the designed sampled-data filter against the same rectangular wave.

improving the sound quality of compressed audio. By that time, I had learned my lessons and had already produced a real-time demonstration. The demo took the optical readout of CD signals, which is processed by upsampling four times (eight times in a later model); see Figure 4.

This time, I was fortunate to have a very enthusiastic collaborator, Mr. Koji Fujiyama, at Sanyo Electric. He was equally convinced that this method opened an entirely new horizon for restoring original analog sounds. However, its production was by no means straightforward. Fujiyama and I were confronted with strong objections, similar to the ones I had heard before. One objection was, "is there an *objective* test to show that the new method sounds better?" This was yet another way of saying that they did not wish to take the risk. If we think about it carefully, there could be no objective test since the answer is ultimately in your own brain.

A turning point came suddenly when Fujiyama heard of a program called PEAQ (Perceptual Evaluation of Audio Quality) [4] that measures perceived audio quality. The sampled-data filter (we later called it the YY filter, rather pretentiously) greatly improved the quality of compressed audio, on average, by about 0.5 to 1, on a scale of 5. Once this was shown, the responses completely changed. After the production of the first test chip started, the new ideas and sound quality were well received by customers, and we were suddenly surrounded by supporters. The total production of these sound processing chips by Sanyo Semiconductor has reached 40 million in the last seven years. The team of my colleague Masaaki Nagahara, Mr. Fujiyama, and I had the honor of receiving the 2012 Transition to Practice Award of the IEEE Control Systems Society.

LESSONS

Well, what lessons did I learn from these experiences? Let me start by listing some reasons for my early failures.

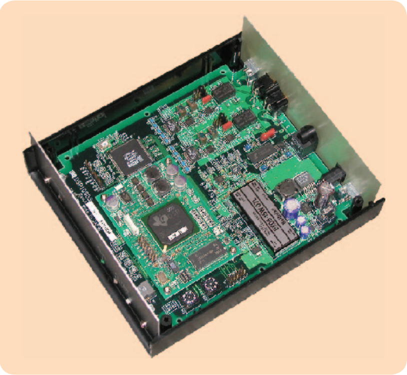

FIGURE 4 A prototype of an oversampling DA converter that processes CD signals and optimally recovers the frequency range up to 175 kHz.

- I assumed that everyone in industry was always very eager to improve upon their products and was looking for opportunities for improvement. The fact is that everyone is only human and, unless success is certain, most people will not risk anything.
- Likewise, unless we provide a real example, no one will believe a new theory. Actual production is often a complex process, and it is not as routine as just implementing an algorithm.

There were some positive factors also:

- I had some previous knowledge about high-end audio and knew what I was talking about. This yielded a strong motivation and played an important role when I had to talk to the people in industry.
- I did not quit. Of course it is discouraging to realize that others do not agree with a good idea of yours. You may need to listen to them to persuade them, but you should not be overly modest. No one knows the future, and no one can tell what it is like. Conviction can make a difference.
- I had to produce an effective demo, using digital signal processors. Someone might say that "listening is believing." Nothing is more convincing than actually experiencing.
- I was lucky enough to have a collaborator who not only understands the idea but even the theory itself. We made a good team.

So what do we have to do to make our theory or idea materialize in reality? From time to time, we get interesting ideas. Some ideas result in a patent. But we should not jump on the dream that the idea or patent will immediately yield a goose laying golden eggs. Many people need to be convinced and many problems need to be solved before the idea gets anywhere near actual production. You have a chance to succeed only when

- your idea is good
- you are determined not to quit
- you try to envision an industrial viewpoint on the value of idea and are able to convince people.

Bringing an idea into practice can be a long and often disappointing, discouraging, or even degrading experience because no one sees the ingenuity of your idea in the first place. However, if you succeed, you will certainly get satisfaction, not only as an engineer who can see the outcome of your invention but also as a theoretician who was able to "close the loop" between theory and practice.

I ventured to write my personal story about the actual production in which I took part. I hope this journey encourages you in making your inventions real.

I welcome your feedback. I can be reached at yy@i.kyoto-u.ac.jp.

Yutaka Yamamoto

REFERENCES

[1] T. Samad and A. M. Annaswamy, Eds. (2010). The impact of control technology. IEEE Control Systems Society. [Online]. Available: http://www.ieeecss.org/general/impact-control-technology

[2] C. E. Shannon, "Communication in the presence of noise," in *Proc. Institute Radio Engineers*, Jan. 1949, vol. 37, no. 1, pp. 10–21.

[3] Y. Yamamoto, M. Nagahara, and P. P. Khargonekar, "Signal reconstruction via H-infinity sampled-data control theory—Beyond the Shannon paradigm," *IEEE Trans. Signal Processing*, vol. 60, no. 2, pp. 613–625, 2012.

[4] PEAQ. [Online]. Available: http://en.wikipedia.org/wiki/PEAQ