Focus on Compressive Sensing

“A unique single-pixel camera inspires a new generation of faster, cheaper imaging technologies.”
—John Edwards

Back in 2004, Rice University researchers Richard Baraniuk and Kevin F. Kelly shook the imaging field, and more than a few accepted notions, by developing the first single-pixel camera. The prototype device demonstrated that a new technique, compressive sensing, provided a practical and relatively inexpensive way of creating high-resolution images in less time and with fewer sensors.

In the years since the single-pixel camera’s introduction, researchers in several technology areas, including consumer and commercial photography, magnetic resonance imaging (MRI), and radar, have begun using compressive sensing to speed imaging, create high-quality images using only a limited number of sensors, or a combination of both attributes. Today, compressive sensing (also sometimes called compressed sensing) is increasingly seen as a way of helping developers enhance a wide range of existing imaging technologies without driving up costs.

The technique is, in essence, a shortcut. “Compressive sensing is really a mathematical basis for estimating a signal when you haven’t made enough measurements,” says David J. Brady, a Duke University electrical and computer engineering professor and compressive sensing researcher. “Basically, you’re trying to estimate more signal values than you measured and it applies, very broadly, to many different measurement systems” (Figure 1).

Baraniuk, Rice’s Victor E. Cameron Professor of Electrical and Computer Engineering, says that the single-pixel camera was the result of a series of extraordinary advances over the previous several years in computational science, particularly signal processing. “[It was] such that we could envision building entirely new kinds of sensors and, in particular, things like cameras that performed far beyond what you would expect using standard theory.”

Baraniuk notes that until the early 21st century, sensor research was largely driven by mathematics developed in the 1940s, primarily by the Shannon-Nyquist sampling theorem. “That theory told us that if you wanted a certain resolution, say in a camera or in an MRI scanner or an analog to digital converter, you had to sample at least twice as fast as the highest frequency in the signal.” The results, he says, were highly predictable and fundamentally inflexible. “If we want a resolution in, say a digital camera of 10 megapixels, the theorem basically tells us that we need 10 million little sensors,” Baraniuk says.

By 2004, however, new theoretical research had arrived to allow developers to push beyond the compression limits dictated by Shannon-Nyquist. “[It] made people realize that if we know just a little bit more about the signals, namely that they’re compressible by an algorithm like JPEG, then you can actually sample the signals at a much, much lower rate,” Baraniuk says. “Our realization was that we could build a camera that had 10 million effective pixels, but had a far fewer number of sensors.”

Baraniuk and Kelly decided to push the new technique to its logical limit. “We took it to the extreme end of things, which was one single pixel, one single sensor,” Baraniuk says. According to Kelly, a Rice associate professor of electrical and computer engineering, a single-pixel camera prototype seemed like an ideal way to both develop the concept...
and to demonstrate compressive sensing’s potential. “Rich and I realized that the best way to realize the mathematics was its direct implementation in hardware platforms,” he says.

Baraniuk notes that while the camera represented a practical use of compressive sensing, the device itself wasn’t the most important thing. “The real discovery was this new signal processing mathematics, which tells us that we can build sensors that take far fewer measurements than the classical theory would tell us,” he says.

The realization led Baraniuk and Kelly to a new understanding of data compression. “It’s commonly thought that if we want a 10-megapixel image, that we need to tap a whole bunch of little sensors on our camera chip, and that’s actually not true,” Baraniuk says. “Likewise, if we think we want a certain resolution with an MRI scan of our brain, that we need to sit in the scanner for 20 minutes. Well, that’s not true, either.”

**COMPRESSED MEDICAL IMAGING**

Michael Lustig, an assistant professor of electrical engineering and computer sciences at the University of California, Berkeley, feels that compressive sensing has the potential to revolutionize MRI technology, opening the door to faster medical imaging and, potentially, even video-style. Lustig is currently engaged in research that aims to make MRI scans better, faster, and more comfortable for patients.

“One of the shortcomings of MRI is that the scan time is relatively long,” Lustig explains. He notes that until compressive sensing came along, MRI researchers were facing a brick wall when it came to reducing the amount of time required to conduct an MRI without seriously impairing resolution quality. “We were really at the limit of being able to collect data as fast as possible, just because of the physical and physiological constraints of the system,” Lustig says.

Lustig feels that compressive sensing provides an almost ideal way of speeding up uncomfortable and claustrophobia-inducing MRI scans, which currently take up to 30 minutes or more. “One of the only ways to accelerate the scan time is to reduce the amount of data that’s needed to reconstruct the image, so when the idea of compressed sensing came about it immediately occurred to us that MRI would be a great application to apply it to,” he says.

Compressive sensing provides an entirely new approach to MRI image reconstruction. “Compressed sensing uses the fact that images are compressible, or that they can be represented expressly after applying some mathematical transformation,” he says. “Up until now, none of the reconstruction techniques took advantage of that fact.”

Lustig adds that compressive sensing can also ensure a higher degree of image integrity than other data compression techniques. “If you consider the fact that the image you’re expecting to reconstruct is compressible, you can reduce the amount of data but still be able to reconstruct the original image almost exactly,” Lustig observes.

Lustig notes that image loss is a much larger concern in medicine than in conventional photography. In medical imaging, patients’ lives often hinge on the inclusion—or omission—of just a few pixels. “That is one of the main issues with compressed sensing: to actually show in the clinical setting that you can robustly collect less data but still be able to get what you’re interested in,” Lustig says.

Compressive sensing can be a relatively low-cost way of improving MRI technology. “You really don’t need to change the hardware,” Lustig says. “It turns out that just by changing the software, and the way we acquire data in an MRI, we can do the kind of random sampling that is needed for compressed sensing.”

Lustig says that most of the cost of using compressive sensing in MRI systems lies in creating the software. “Because, if you have an MRI system, you’ll be able to do compressive sensing just by changing the pulse sequences…basically just by changing the software.”

Most of the major MRI vendors are now working to add compressive sensing software to their systems. “I know GE has a team working on it, so do Siemens and Philips,” Lustig says.

Lustig’s University of California, Berkeley, team is also striving to bring compressive sensing MRI machines into the real world. “We have a project at Lucile Packard Children’s Hospital [in Palo Alto, California],” he says. “We’re trying to use this technique to accelerate the [scanning] of pediatric patients.”

Infants are among the most problematic MRI patients. “This is a very vulnerable population, and they’re very hard to image with MRI,” Lustig says. “Because of the long scan times, they have to be put under general anesthesia.” In an effort to reduce or even eliminate the need for anesthesia, the researchers are working with the hospital’s pediatric radiologists to cut scanning times to the absolute minimum. “So if something would have taken two or ten minutes, then it might be reduced to maybe 20 seconds or just a minute instead of the full exam time, Lustig says.

After the data is acquired, it’s sent to a “reconstruction machine,” a computer equipped with high-speed general-purpose graphics processors. “Basically, it’s a lot of very powerful processors to process the data very quickly,” Lustig says. “Within less than a minute, you get images showing on your screen.”

Stretching compressing sensing’s limits requires a great deal of caution, however. “You have to be careful not to push the technology too much, because then you’ll start degrading the image quality,” Lustig says. Fortunately, errors are relatively easy to detect. “A trained radiologist, when he looks at images, he kind of knows if he’s seeing something that looks like an artifact [or] if it’s too low resolution,” Lustig says.

Despite ongoing improvements, image reconstruction time continues to be an important issue. “It used to take several hours to reconstruct a simple three-dimensional (3-D) volume; we’ve been trying to address that by using parallel computing and fast algorithms,” Lustig says. “We’re now able to go just below a minute for reconstruction, but that’s just for static images.”

Lustig now wants to use faster MRI scanning rates to create 3-D MRI movies. “There are a lot of exams where you
inject a contrast solution into the body and you want to follow that contrast and to see it work dynamically,” he says. “You mostly think of [MRI] as a still camera, but what we’d like to do is make it more like a video camera.”

Creating full-motion MRIs will be a challenge however. “The problems are just huge … incredible,” Lustig says. “We’re talking about billions of variables to solve in order to get the images and huge amounts of memory.”

A typical single, static MRI exam currently generates about five or six gigabytes of data, Lustig says. But an entire sequence of MRI images would boost storage requirements by several magnitudes. “We’re talking about dynamics that can go up to hundreds of gigabytes,” Lustig says. While that’s not very much data in a world where 1 TB hard drives sell for under $100, reliably processing all of that information within a reasonable amount of time, even with the help of the most sophisticated compressive sensing techniques running on the most powerful processors, could result in very long processing times for both MRI systems and patients.

While MRI video remains on the drawing board, Lustig expects that basic, static compressive sensing MRI technology will become widely available over the next several years. “I think you’ll see this kind of technology appearing in clinical practice in some form,” he says. “It may not be the exact, true compressed sensing that was described in the theoretical papers, but a lot of these ideas will definitely penetrate [and] we’ll be able to get much faster scans that produce much higher quality just by using these ideas.”

ON THE RADAR SCREEN
Radar is another technology that could potentially benefit from compressed sensing. “One of the more high profile compressed sensing projects going on right now is building … a new radar receiver that can operate at very high frequencies,” says Justin Romberg, an assistant professor of electrical and computer engineering at Georgia Tech. Romberg is investigating how the technique can be used to improve radar performance while cutting system costs. Teams at Cal Tech and Rice are also participating in the research, which is being funded by DARPA.

“The main thing all the different compressive sensing projects have in common is that you encode or scramble the data before you sample it,” Romberg explains. “Rich [Baraniuk] does that with the single-pixel camera through using a mirror array; we do that for our radar receivers using high-frequency modulators,” Romberg says. “They’re just very different physical instantiations of the same principle.”

The new receiver is being designed to bring high-frequency radar technology into the digital age. “It’s impossible to build traditional hardware that acquires [radar pulses] digitally,” Romberg says. “You have to basically build expensive analog circuits to see what’s out there,” he states.

Scrambling data with compressive sensing paves the way for cutting costs. “If you put this kind of scrambling on the front end, you can use more traditional acquisitions and still work your way into these high frequencies,” Romberg says. “So the idea is to build cheaper hardware that lets you access more of the spectrum.”

As the receiver researchers experiment with and refine various compressive sensing approaches, they’re looking to achieve a technology balance. “It requires … effort to tease the information that you want out of the data that you’ve taken, so you might have to have a little more advanced processing algorithms on the back end,” Romberg says. “It’s like we’re sort of trading off front-end sensor complexity versus back-end computing.”

Romberg says he’s excited by compressive sensing’s potential to provide low cost, high speed analog to digital conversion. “It can allow you to reach parts of the spectrum, high frequencies, that you just can’t get with any kind of traditional hardware,” he says. “I mean, they’re just totally inaccessible right now, except with some very expensive [hardware].”

A possible application Romberg and other researchers are looking at is ground penetrating radar. “When you’re sweeping an area for land mines, for example, it takes a while to create a scan of the entire area,” he says. “What this [compressive sensing technology] will do is reduce the amount of time that the scanning will take.”

Besides radar, compressive sensing has a wide range of other potential communication applications, Romberg says. “There are people who are very interested in using these same types of ideas for very low power communications,” he says. “You can have sensor networks that operate over a very long time period without having to have their batteries recharged.” Romberg says there’s also a chance that the technology might be integrated into next-generation analog-to-digital converters. “It could actually appear in, say, your cell phone,” he says.

DOWN THE ROAD
Widespread commercialization of compressive sensing technologies is only a matter of time, predicts Baraniuk, who serves as a director of InView Technology, a company that he cofounded with Kelly to develop and market compressive sensing camera products. The Austin, Texas-based firm is currently developing a series of infrared cameras that it promises will be anywhere from five to ten times cheaper than currently available counterparts.

Brady is also bullish on compressive sensing’s commercial prospects. “I think it’s certainly going to come very soon,” he predicts. Brady sees compressive sensing technology popping up in multiple areas. “The main markets are security markets, consumer imaging markets, and machine vision things,” he says.

Baraniuk, meanwhile, thinks that space could be compressive sensing’s next frontier. He sees cameras based on the technology being used on space probes to analyze alien environments. “That’s something that’s available today through hyperspectral cameras—but they cost hundreds of thousands of dollars,” Baraniuk says. “We hope, and plan, to be able to build one of these [cameras] for thousands of dollars.”