John Edwards

Signal Processing Opens New Views on Imaging

The importance of signal processing in imaging is growing rapidly as technologies continue to develop and mature and as various fields begin to recognize the value of innovative new imaging and image analysis systems. By enabling people to clearly observe and detect things that are not ordinarily visible or not readily apparent to the unaided eye, signal processing-driven imaging technologies are helping to save lives and property from hazards lurking both on the ground and below the earth's surface.

TURNING THE CORNER

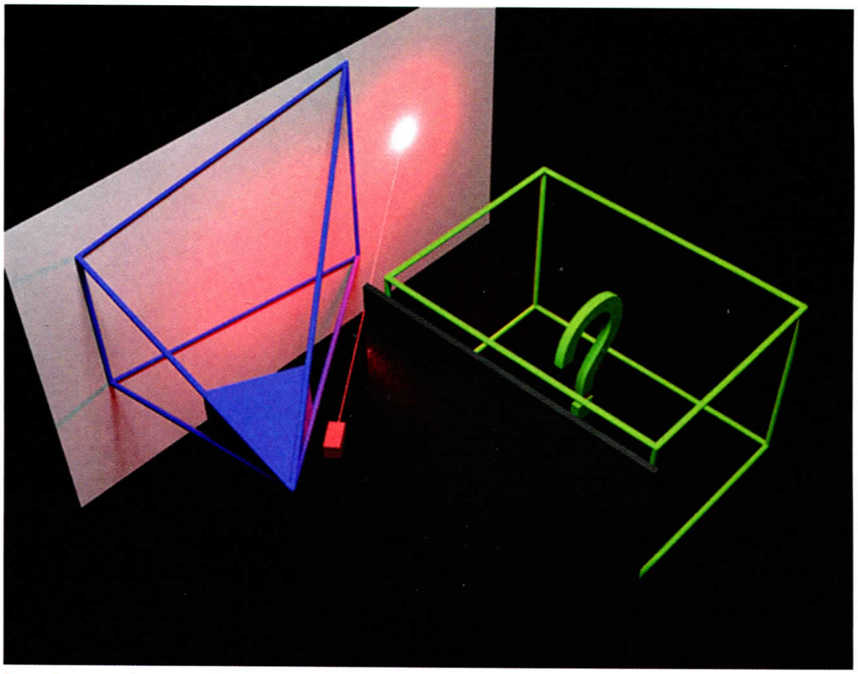
Researchers often claim that they have "turned the corner" whenever they make a major advancement or reach a new level of understanding in their work. Yet, scientists at the University of Bonn and the University of British Columbia can uniquely claim that they have developed an imaging technology that is specifically designed to turn its field of view around corners to see objects that would otherwise remain hidden from view. Their new camera system is designed to see around bends and turns without any help from a mirror. Using diffusely reflected light, the new camera can reconstruct the shape of objects located far outside of the field of view of human eyes and ordinary cameras.

"Being able to look around corners can potentially benefit a range of applications, from traffic safety to search and rescue operations," says Matthias B. Hullin, a professor at the University of Bonn's Institute for Computer Science. To image objects that are blocked to human viewers by walls or other physical obstacles, the camera shines a laser dot on a nearby vertical surface and then records both the direction of the light and the time it takes to reach the camera's imaging sensor (Figure 1). As the image is processed and reprocessed, the outline of the object the camera is trying to see becomes apparent to the viewer [see (Figure 2(a) and (b)].

SIGNAL PROCESSING-DRIVEN IMAGING TECHNOLOGIES ARE HELPING TO SAVE LIVES AND PROPERTY FROM HAZARDS LURKING BOTH ON THE GROUND AND BELOW THE EARTH'S SURFACE.

"We are recording what is essentially a light echo, and the time-resolved data allows us to reconstruct the object," Hullin explains. "Part of the light has also come into contact with the unknown object, carrying with it essential information about its shape and appearance."

The system takes advantage of multipath scattering interference. The approach is directly opposite to standard practice in telecommunications and remote sensing, where multipath in most applications is considered an annoyance rather than a source of additional data. "The key insight from our work is that, using accurate models for multipath scattering, a lot of information...can be



MATTHIAS B. HULLIN, UNIVERSITY OF BONN.

[FIG1] A rendering of the imaging scenario. The light source (red) and camera (field of view marked in blue) both look at a white wall. The objects to be captured in a reconstructed image (green box) are hidden behind an occluder and are only accessible through indirect reflections off of the diffuse wall.

Digital Object Identifier 10.1109/MSP.2015.2437291
Date of publication: 13 August 2015

1053-5888/15©2015IEEE

unlocked that is not contained in the direct reflection," Hullin says.

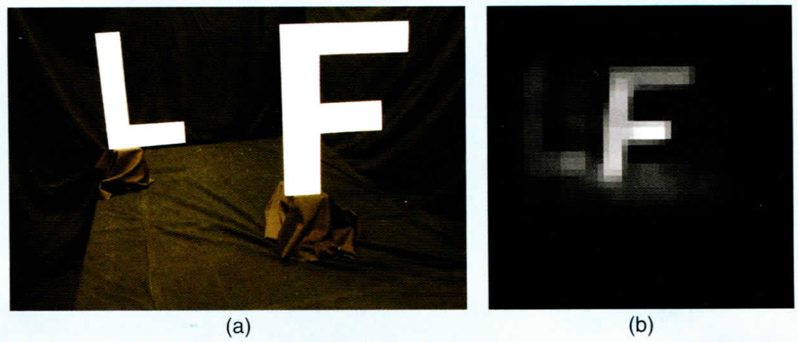
The method, Hullin explains, is based on space-time impulse responses of light. "Imagers with sub-nanosecond temporal resolution...are rare, expensive, and unpractical, so experimental results were out of reach until we found a way to circumvent the need for high-end gear."

To circumvent the cost problem, the researchers settled on a type of camera that long ago entered the mass market: a Creative Senz3D, which currently sells for about US$115. The "time-of-flight" camera resolves distance based on the known speed of light, measuring the time-of-flight of a light signal between the camera's sensor and the subject for each point of the image.

Yet, before the inexpensive camera could begin imaging around corners, it required significant modification. "It is surprisingly challenging to find research-grade hardware that offers free choice of modulation frequencies and raw data readout," Hullin says. "To construct our imaging system, we therefore had to hack into a time-of-flight development board, literally drilling into the sensor chip to combine it with a custom signal generator."

Signal processing is central to the project. "Light transport and image sensors are linear time-invariant systems, so we can draw from a rich pool of signal processing methodologies to deal with the data at hand," Hullin remarks. "Nothing we do would be possible without the help of compressed sensing."

Hullin notes that the challenge of imaging around corners is not unlike trying to enhance a poorly focused conventional photograph. "In many ways, what we want to achieve is closely related to the problem of deblurring an image," he says. "Once certain



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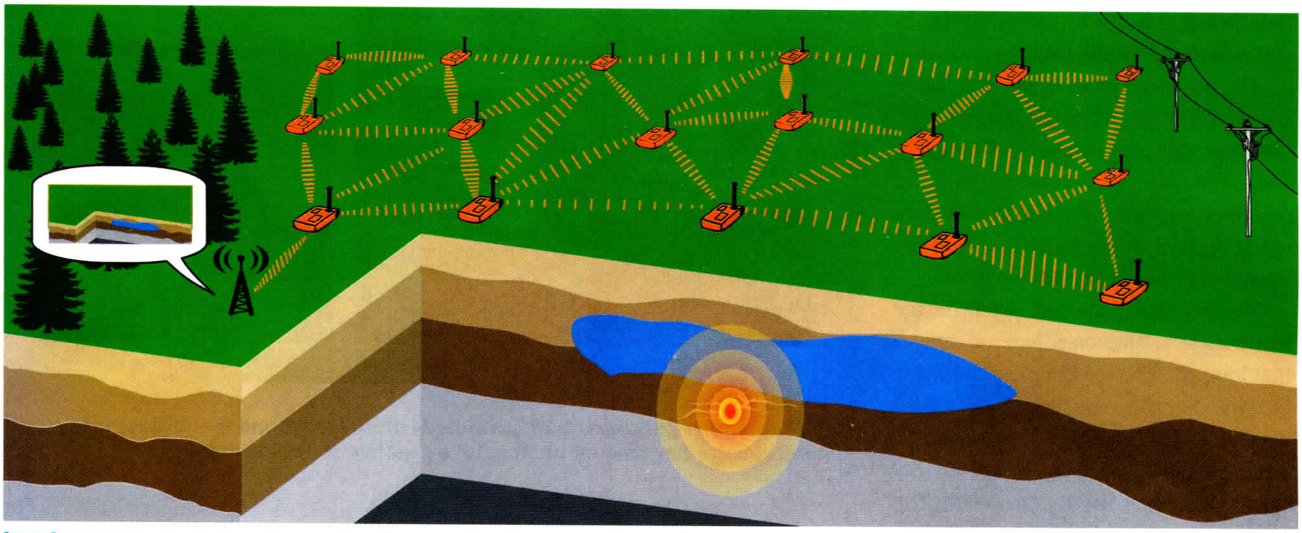
[FIG2] A regular photograph of cardboard cutout letters and the reconstructed indirect image captured by the modified Creative Senz3D camera.



[FIG3] An RISI seismic imaging system in a passive layout configuration.

frequency bands have been destroyed by blur, plausible reconstructions can only be obtained by making additional assumptions about the signal we are interested in."

Image deblurring is often formulated as a least-squares optimization problem regularized with a total-variation gradient penalty to avoid unnecessary structure within the image. Hullin says his team models hidden scenes as a volumetric distribution of scattering densities. Then, using a combination of sparsity priors, they constrain the solution space to solutions that are zero almost everywhere except at object surfaces. "In other words, opaque objects are preferred over 'cloud-like' ones," Hullin says. "As is often the case when using compressed sensing methods, we found development of good prior models the most challenging task," he adds.

"The accuracy of our method has its limits," Hullin admits. Imaging remains restricted to rough outlines. Yet, the researchers believe that the rapid development of technical components and mathematical models will soon allow a higher resolution to be achieved. A similar around-the-corner imaging technology developed at the Massachusetts Institute of Technology (MIT), using direct reflection of lasers creates similar results: blurry, yet discernible images of objects from outside the camera's field of view.

Another challenge, Hullin says, is making the system real-time capable. "So far, we need to capture hundreds of individual input images and the reconstruction takes hours to complete," he says. In an early prototype, a student has been able to demonstrate that objects can be detected and tracked around a corner within a few milliseconds per frame.

HULLIN NOTES THAT THE CHALLENGE OF IMAGING AROUND CORNERS IS NOT UNLIKE TRYING TO ENHANCE A POORLY FOCUSED CONVENTIONAL PHOTOGRAPH.

The new imaging technology is already generating interest from various commercial and government organizations. "We are in touch with people from various industries including automotive, defense, and entertainment," Hullin says.

IMAGING HIDDEN DANGERS

Wen Zhan Song, a Georgia State University computer science professor, wants to get a picture of what is happening underground with the help of a real-time seismic imaging system that uses ambient noise to reveal shallow earth geologic structures in detail. The system promises to allow users to study and monitor the sustainability of an area's subsurface as well as pinpoint potential hazards hidden inside geological structures. Song and his collaborators, Yao Xie of the Georgia Institute of Technology and Fan-Chi Lin of the University of Utah, are planning to test their system by imaging the subsurface of geysers in Yellowstone National Park.

The technology is designed to create images of underground structures in settings where there is no active source, such as earth tremors. "We're using background noise," Song says. At Yellowstone, for instance, vibrations created by visitors and their cars feed the system. "We essentially use that type of information to tap into a very weak signal to infer the image of [what is] underground," Song explains.

The real-time in situ seismic imaging (RISI) technology images and monitors subsurface geophysical structures and dynamics in real time. "An RISI system is a wireless seismic network that senses and processes seismic noises from natural earthquakes and oil/gas exploration and production activities," Song says. "Instead of collecting data to a central place for postprocessing, the distributed seismic data processing and tomographic computing are performed in the in situ network and the evolving 3-D image is computed and delivered in real-time for visualization" (Figure 3).

Each solar-powered RISI station is equipped with an Advanced RISC Machine-based microprocessor, a mesh network

UNIVERSITY OF DAYTON.

[FIG4] **Image enhancement allows the extraction of additional details within the target area, enabling the automated surveillance technology to accurately detect and classify objects that pose a possible threat to a nearby pipeline.**

transceiver, a global positioning system (GPS) receiver, and a geophone, a device that converts ground movement (displacement) into voltage. Each station is capable of acquiring and processing data, and communicating with other nearby RISI stations, via the mesh network.

Song says that RISI promises to be useful in a wide range of georelated applications, including oil and gas exploration and production, safety and environmental surveillance, and volcano, landslide, and earthquake monitoring. "It can provide real-time awareness—in less than a second—of oil/gas exploration and production processes and potential subsurface hazards so that certain mitigation or optimization action can be taken promptly," he notes. The technology could also be used to alert homeowners to a subsurface change below their residence, an indication that their house may be sinking.

According to Song, ambient seismic events generally have an extremely low signal-to-noise ratio (SNR), mandating the use of a noise suppression algorithm. Yet even after denoising, the SNR of specific events may remain too low for reliable interpretation. "In ambient noise seismic imaging, it is basically impossible to identify events from individual data streams," Song says. A cross-correlation among different seismic channels and data streams is often needed to identify the events window and find the relative time difference. "The cross-correlation based signal processing needs to be done in a distributed fashion and under severe communication constraints," Song notes.

Song is optimistic the RISI has significant scientific and commercial potential. "We are helping industry lower costs greatly, because previously they only knew what was going on in the subsurface only days or even months later and we can reduce this time to just seconds," he says.

"We are essentially making automatic and fast video cameras for 3D/4D subsurface images while existing industry techniques and practices are [comparable to] manual painting with paintbrushes," Song says.

IMAGE ANALYSIS OF PIPELINE THREATS

Millions of kilometers of pipelines lay buried underground worldwide, transporting water, fuel and other types of essential liquids and gasses. All of these pipelines are vulnerable to breach by various types of construction and drilling activities. Unintentional pipeline damage often has serious and immediate consequences, including explosions, environmental contamination and the interruption of vital services. To lower the risk of pipeline damage, pipeline property owners must often limit or outright prohibit other activities on their land.

Recent advances in sensor technologies have led to the use of aircraft-based video acquisition systems to monitor activities on vulnerable properties. Such systems, however, typically generate massive amounts of data that human analysts must pore over visually to identify pipeline right-of-way threats. The process is both expensive and time-consuming.

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ACKNOWLEDGMENTS

We wish to express our gratitude to Prof. Fulvio Gini, *IEEE Signal Processing Magazine's* then-area editor of special issues, for the support and advice provided throughout the preparation of this special section. We also thank Rebecca Wollman, IEEE Signal Processing Society publications administrator, for her valuable assistance. Finally, we acknowledge the many anonymous reviewers whose outstanding contributions have ensured and helped to enhance the quality of the articles that follow.

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special REPORTS (continued from page 11)

Using multiple object detection and recognition algorithms, a research team led by K. Vijayan Asari, an electrical and computer engineering professor at the University of Dayton in Ohio, has developed an automated surveillance technique that can be used to protect underground pipeline infrastructures (Figure 4).

The framework consists of three parts. The first part removes imagery that are not considered to be a threat to the pipeline. The method extracts a set of features that precisely represent the shape, structure and texture of various backgrounds, such as trees, buildings, roads and farmland, using a cascade of classifiers to eliminate the insignificant regions. The second part of the framework is a part-based object detection model for searching specific targets that are considered to be threat objects. The third part of the framework assesses the severity of pipeline threats by calculating the location and the temperature information of threat objects, such as construction equipment or drilling gear. "With our approach we can take into account the constraints associated with aerial imagery, such as low resolution, lower frame rate, large variations in illumination, and motion blurs," says Asari, who is also the director of the University of Dayton Vision Lab.

A major challenge to accurate threat detection are objects of interest that are partially occluded by shrubs, trees, buildings and other terrestrial elements. In the part-based model, an object is partitioned into a specific number of parts; the size of each part depends on the size of the object. "We then use local phase information to extract informative attributes for describing the individual parts," Asari says. "The next step is to group the object parts into several clusters. "In this process, we group similar parts into the same cluster and a histogram of oriented phase is used to describe the specific pattern of the parts," Asari continues. "This is to group similar parts of different vehicles, or similar parts in different images of the same vehicle, into the same cluster or category to find the presence of such categories in an occluded image to detect it as a threat object."

A MAJOR CHALLENGE TO ACCURATE THREAT DETECTION ARE OBJECTS OF INTEREST THAT ARE PARTIALLY OCCLUDED BY SHRUBS, TREES, BUILDINGS AND OTHER TERRESTRIAL ELEMENTS.

The output of the part-based object detection technique is the pixel location of the threat object in the input image. In real-world applications, however, a system user must also know the exact geographic location of a potentially threatening object. A registration process that links the acquired images to a geographical map provides this capability. Additionally, some detected threats may be far away from a pipeline, or have some other type of low threat probability. "Considering these issues, we have designed an additional framework that can automatically analyze the geolocation and temperature information of a detected object, and can assign a risk level to any given threat—high, medium, or low," Asari says. "A high temperature indicates that the vehicle is active and it may be moving to the pipeline right-of-way; a low temperature indicates that the vehicle is stationary and is of low risk."

"We have reached over 85% accuracy for machinery threat detection in tests," Asari says. "We are confident that our method can be used as a practical approach for wide-area surveillance and to protect pipeline infrastructures."

Asari says that he and his team are currently focusing on hardware-software integration and performance acceleration aspects. "We are looking to enable real-time processing in an onboard flight environment," he remarks.

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