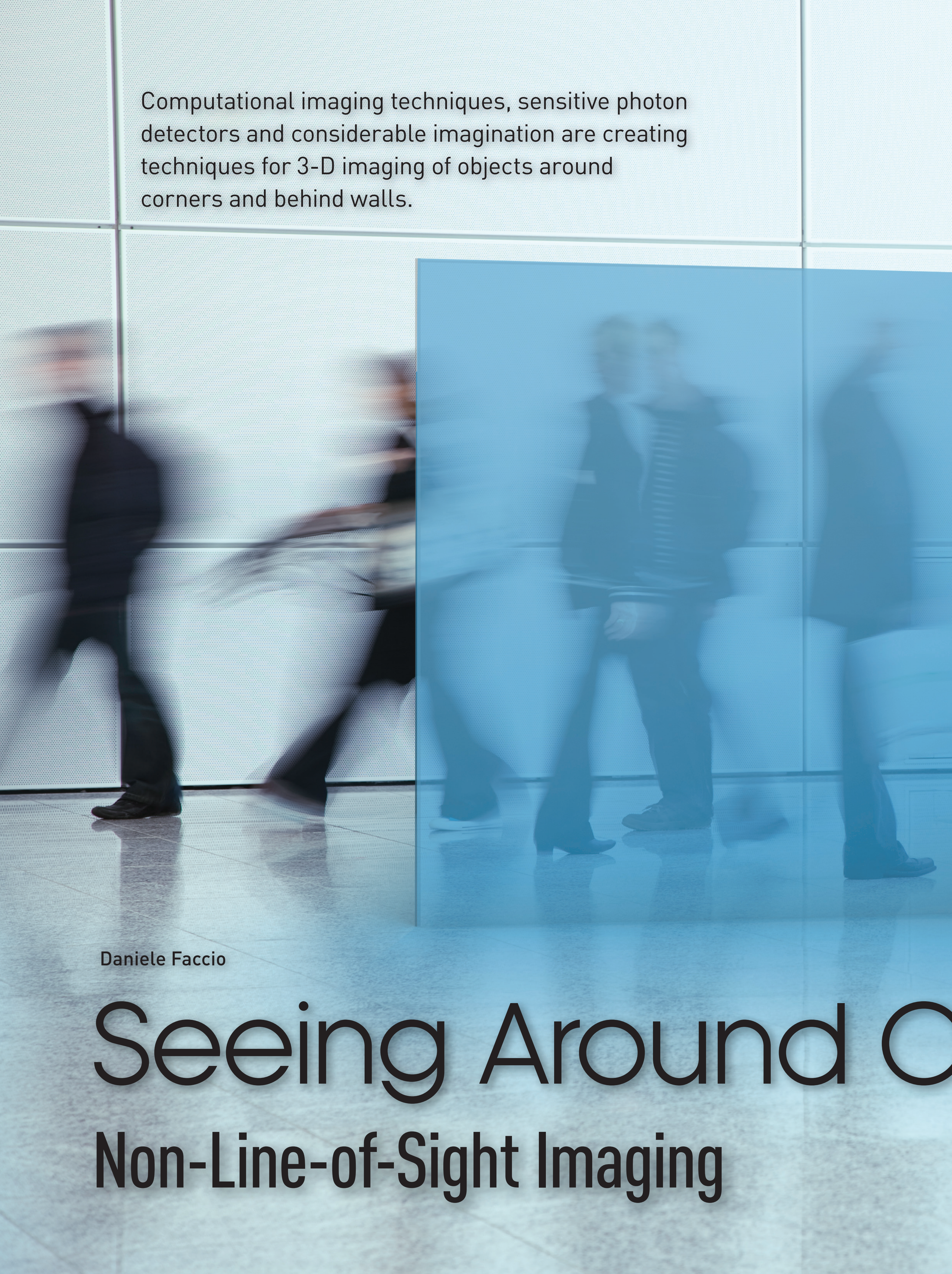
Computational imaging techniques, sensitive photon detectors and considerable imagination are creating techniques for 3-D imaging of objects around corners and behind walls.



Daniele Faccio

Seeing Around C

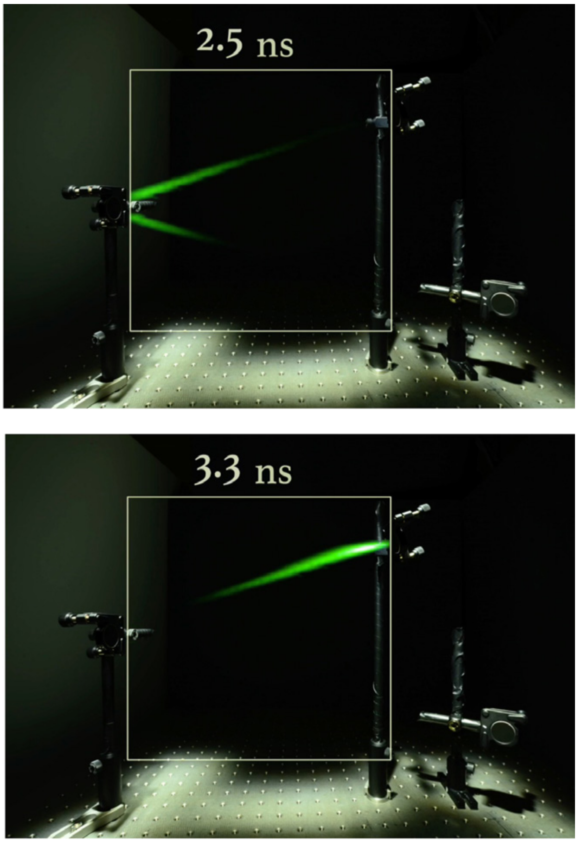
Non-Line-of-Sight Imaging

Corners

Background: Getty Images /
Composite image: Alessia Kirkland

Light travels in straight lines. This simple observation was the basis, in the 17th century, for Isaac Newton's corpuscular theory of light. In the absence of any external force, particles travel in straight lines, so a "particle" theory of light, such as Newton's, can capture much of what we see in our everyday experience.

We now know, of course, that things are slightly more complicated than that. Thomas Young and James Clerk Maxwell showed that light propagates as a wave. And then, somewhat ironically, experiments by Heinrich Hertz that proved Maxwell's equations to be correct also provided the first hints of the photoelectric effect. The explanation for that effect—that light–matter interaction is quantized—earned Albert Einstein his Nobel Prize in Physics, and showed that light, while wave-like, is also made up of individual, particle-like photons.



Light in flight

Two snapshots of a 500-ps, 532-nm laser pulse captured in flight as it propagates in free space between two mirrors. The white square indicates the area imaged by the SPAD camera. The background scene is taken with a standard DSLR camera.

Hence the fundamental observation and starting point for Newton's reasoning remains true: photons do not propagate in curved lines. All of our textbook ray-tracing discussions about how images form would look very different in a world in which light could bend and curve. Granted, astrophysicists enjoy a glimpse of such a world through the phenomenon of gravitational lensing, in which a gravitational field can effectively bend the propagation direction of light as seen by a distant observer—thereby allowing a telescope on Earth to observe stars and objects otherwise hidden (for example, by a distant galaxy) from the direct, Euclidean line of sight. Such lensing, however, requires huge gravitational forces and propagation over astronomical distances.

Here on Earth, we are still bound by the geometrical description of light rays propagating in straight lines. Yet researchers have worked intensely in recent years on methods that allow, within the constraint of straight light rays, the imaging of objects behind obstacles and around corners, developing some remarkable imaging technologies and applications in a range of fields.

Capturing light in flight

This story starts with the first attempts to capture ultrashort bursts or pulses of light as these propagate through an experiment or through a scene—developments that paved the way for the sensitive light detection used in non-line-of-sight (NLOS) imaging.

The first techniques aimed at time-gated imaging of a scene were based on mechanical, electronic and stroboscope approaches that can provide microsecond temporal resolution. Such resolution is sufficient, for example, to freeze the motion of a supersonic bullet, as pioneered in the remarkable stroboscopic photographs by OSA Fellow Harold Edgerton of the Massachusetts Institute of Technology, USA, beginning in the late 1930s. But this is far from the million-fold increase in temporal resolution required to freeze the motion of a light pulse.

The first attempts to do that date back to pioneering work at Bell Labs in the late 1960s, where laser pulses were used to optically control a nonlinear material that could act as an ultrafast gate placed in front of a camera. Similar pump-probe techniques are now widely used in most ultrafast-optics laboratories around the world, and have become a cornerstone of chemical and condensed-matter spectroscopy.

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Researchers have worked intensely in recent years on methods that allow the imaging of objects behind obstacles and around corners.

OSA Fellow Nils Abramson, a holography pioneer working at the Royal Institute of Technology, Sweden, in the 1970s, approached the problem from a conceptually different viewpoint. No longer interested in observing ultrafast laser pulse dynamics, Abramson focused on capturing light as it propagates through a natural scene—for example, light bouncing off a mirror or propagating in a room. He based his approach on an elegant variation of holography, in which the light pulse reflected from the natural scene is made to interfere with a reference pulse on a photographic plate (as in standard holography), with the reference pulse propagating at an angle.

The reference pulse therefore intersects the photographic plate in different positions at different times. The result is a hologram that, when viewed at different positions on the plate, reproduces the scene at different times, with picosecond resolution. Abramson's holograms from the early 1970s are—together with the high-speed movies created nearly 100 years earlier by Eadweard Muybridge—among the most remarkable photographic-film-based scientific achievements of all time.

From ultrafast imaging to imaging behind walls

Moving forward nearly 40 years, Ramesh Raskar delivered a TED talk—based on a paper presented at the 2011 meeting of the Association of Computing Machinery's Special Interest Group on Computer Graphics and Interactive Technologies (SIGGRAPH)—that captured the imagination of many (including the author of this feature). The paper, "Slow art with a trillion frames per second camera," explicitly alluded to Edgerton's work combining art with technology. In his talk, Raskar presented a digital video of a light pulse propagating inside a soda bottle filled with water, showing exquisite details and even relativistic distortion effects of the refracted light. The image had been captured using a streak camera—a camera for imaging ultrafast pulses that relies on a photocathode

Sample applications for non-line-of-sight imaging

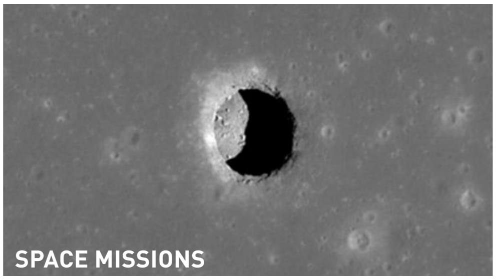
Getty Images

The ability to see around corners could find applications in future self-driving cars, allowing cars to have awareness of approaching vehicles or people well before they are directly visible.

Getty Images

Rescue or military missions will be able to rely on the ability to detect the presence of people inside a room without actually needing to enter it.

NASA



NASA even conducted a study (PERISCOPE) to determine whether the technology can remotely provide information about the inner structure of lava tubes on the moon or remote planets from orbiting satellites. These could one day be candidate sites for future human settlements.

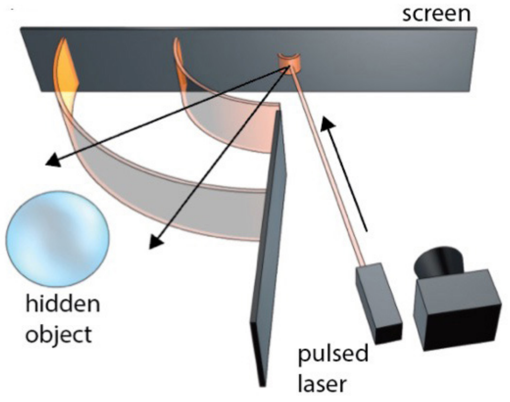
to turn photons into electrons. These electrons pass between a pair of electrodes and can thus be swept across a screen, mapping different temporal sections onto different spatial positions.

Our group, then at Heriot-Watt University, U.K., and in collaboration with the University of Edinburgh, U.K., subsequently developed this further with the use of single-photon avalanche photodiode (SPAD) array cameras. These cameras allowed us to capture the flight of picosecond and femtosecond pulses of light in real time (for example, with capture times of the order of one second), propagating in air (that is, without the need for additional scattering agents, as had been required in all previous studies). The work, which featured videos of light propagating in free space, effectively introduced SPAD detectors to the high-speed-imaging scene. The SPAD detectors also offered a promising route toward real-time 3-D imaging of objects that are hidden from view—a problem that, as will be seen, hinges critically on dealing with a severely limited photon budget.

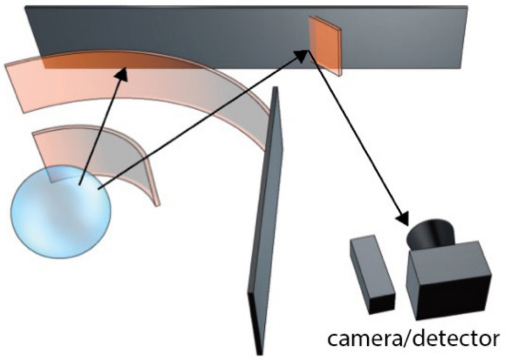
Returning to the problem in 2012, Raskar's group, in a paper led by Andreas Velten, showed that it is possible to reconstruct a full 3-D image of an object hidden behind a wall. In these experiments, the team used a streak camera to image faint "echoes" of light reflected from the hidden scene. In this setup, laser pulses directed at the screen scatter off of it, diffusing light behind the wall and illuminating the hidden object; this object, in turn, reflects the light back toward the screen on to an area that is visible from the general location of the laser and can thus be picked up by the streak camera.

If the hidden object is a small sphere, for example, the returned scattered signal seen by the camera can be visualized as an expanding spherical wave, as if it were originating from a point-like spherical source placed behind the wall. Simplifying the concept still further, the shape of the expanding spherical light intersecting the wall and imaged by the camera—for example, the direction in which the sphere propagates—will give direct information of the spatial coordinates of the hidden object. Moreover, the time of flight measured for the light pulse to leave the laser and finally return back to the field of view of the camera provides a measurement of the distance of the object behind the wall.

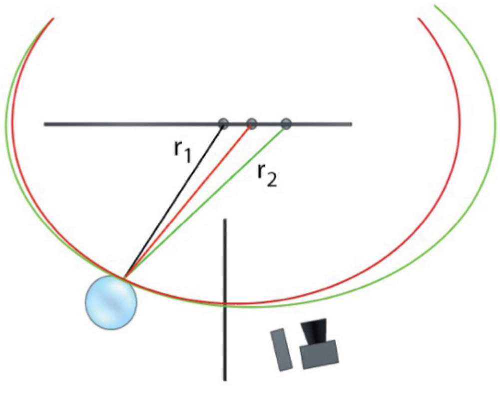
How to image behind a wall



1. Scattered light from laser pulses on a screen propagates behind the wall into the hidden scene



2. Hidden objects scatter light back toward the screen; the detector then measures the arrival time, *t*, of the return signal for a given position on the screen



3. Time-of-flight information is used to reconstruct a series of ellipsoids that all overlap at the position of the hidden object

A complicated object can be thought of simply as an ensemble of voxels—that is, small individual scatterers, each providing its own signal that together will add up in the final camera image.

Building up complexity

More complicated objects than spheres can be thought of simply as an ensemble of voxels—that is, small individual scatterers, each providing its own signal that together will add up in the final camera image. Combining the information of all these signals, it is possible to build a full 3-D image of the hidden object.

A common approach to reconstructing the location of a voxel that originates a signal from behind a wall is back-projection. In essence, the time-of-flight (t) measured by the camera is related to the distance of the voxel/object from the laser spot on the first wall (r_1) and the distance of the voxel/object from the observation point on the wall (r_2): $r_1 + r_2 = tc$, where c is the speed of light. This equation describes an ellipsoid, with the laser spot and observation point as the foci and the overall size determined by the time-of-flight distance of the object, tc.

This single ellipsoid provides an estimate of all possible points that could have originated the signal observed on the screen at time t. By then either moving the laser spot to different positions or, equivalently, repeating the measurement for multiple observation spots, one can reconstruct a series of ellipsoids, all of which overlap at the common voxel/object that originated the return signals. How all these ellipsoids are used largely depends on the choice of reconstruction algorithm or on the kind of information being searched for. Full 3-D reconstruction of a hidden object can be obtained by adding all of the ellipsoids together and then applying filters to threshold and "sharpen" the result.

Alternatively, if one is interested simply in detecting the presence and motion of a hidden object, then a multiplication of the ellipsoids will provide an estimate of object location with minimal computational effort. This approach was used by our group to provide the first real-time measurements of a hidden object, first in the lab and then of humans located around corners more than 50 m away from the detection system.

Alongside the relaxed computational requirements, a number of other factors make the location and tracking of an object easier than full 3-D imaging. Locating an object is essentially a triangulation problem; hence, only three detection points are required. If one can make an assumption about the target object—for example, that it's a human or a car that will therefore have a fixed height—only two detection points will serve to locate the object's position in the horizontal plane. This removes the need for any form of scanning; measurements can be updated at 1 Hz or faster rates.

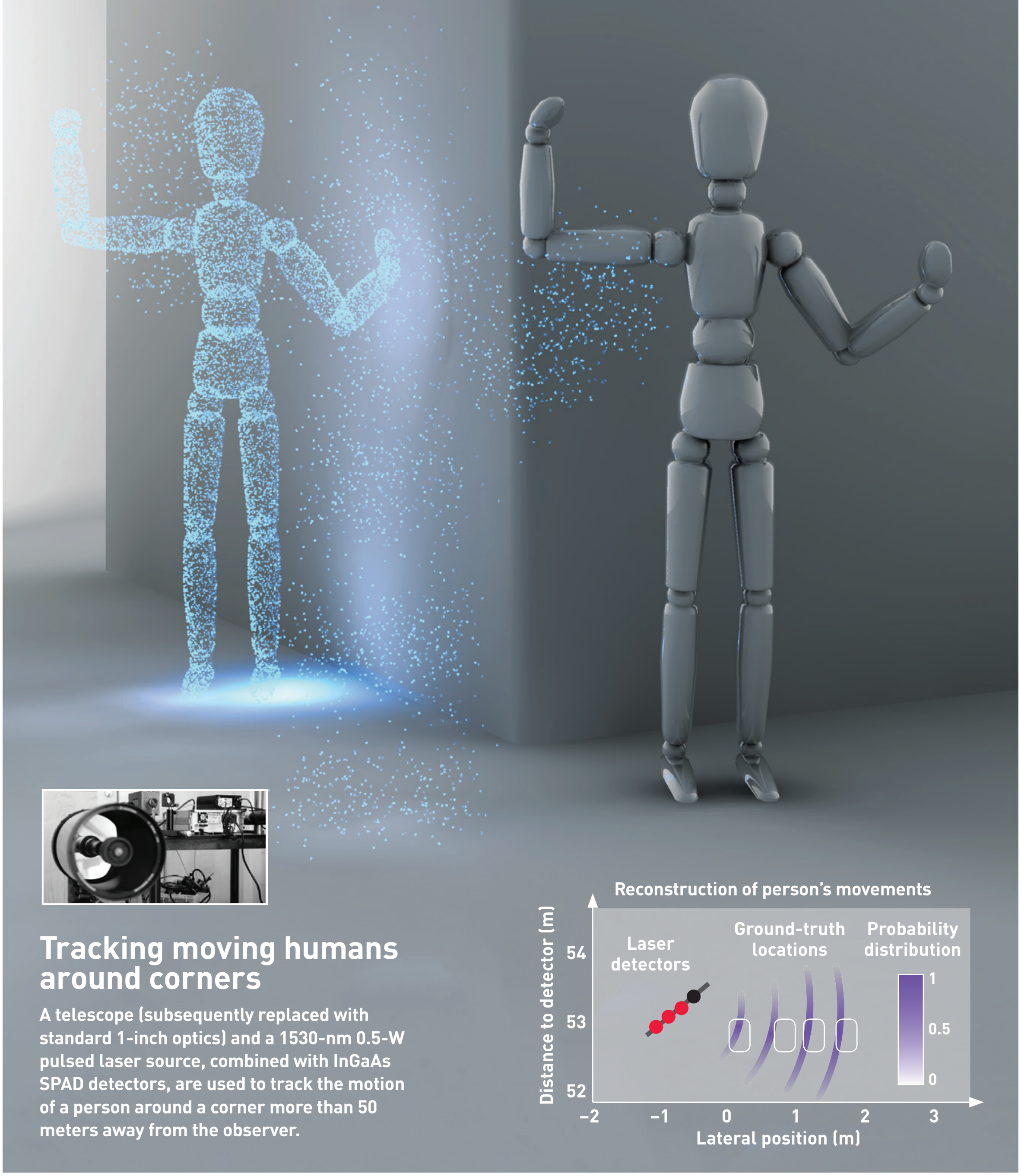
Recent developments by Matthew O'Toole and colleagues at Stanford University, Calif., USA, that combined a simplified retrieval approach with a confocal lidar-like transceiver (that is, one that co-aligns the laser beam and detection) showed full 3-D reconstruction of hidden objects in second time scales. This could introduce a paradigm change compared with the several hours of data acquisition and processing of the original streak-camera approach of Velten and colleagues, published only six years earlier.

Photon budget: The SPAD advantage

All of these techniques ultimately face the problem of the total photon budget. The return signal to the detector results from two consecutive scattering events—that is, the signal decays as $1/r_1^2r_2^2$. This leads to a severe photon loss—one that scales so badly that simply turning up the laser power offers little help.

For example, a typical long-range experiment would use a femtosecond- or picosecond-pulsed, MHz-repetition-rate laser with an average power of 0.5 W, corresponding to roughly 10^{18} photons per second at the laser source. Only 10^3 to 10^4 photons per second are detected in the return signal, which implies significantly less than one return photon per laser pulse, and a loss of order of 10^{12}. To significantly increase the return photons so that, for example, photon-counting equipment would no longer be necessary, the laser power would need to be increased by three to four orders of magnitude—a proposition that creates its own problems.

This highlights the key role played by single-photon detection capability in moving these imaging



Tracking moving humans around corners

A telescope (subsequently replaced with standard 1-inch optics) and a 1530-nm 0.5-W pulsed laser source, combined with InGaAs SPAD detectors, are used to track the motion of a person around a corner more than 50 meters away from the observer.

Illustration by Ella Marushchenko; insets: adapted from S. Chan et al., Opt. Express **25**, 10109 (2017)

applications forward. Fortunately, SPAD technology is mature and is available also in arrayed detectors with sub-100-ps temporal resolutions. As can be intuitively seen from the ellipsoid equation discussed earlier, the detector's temporal resolution will determine the retrieved 3-D image's spatial resolution: 100-ps temporal resolution can provide roughly 1.5-cm distance (and therefore shape) resolution. That is sufficient for most large area objects, and should make it possible to distinguish between main object categories—for example, between a human being, a car and a table.

In recent work, our group took a slightly different approach to determining the shape of a hidden object. If the object shape is encoded in the temporal distribution of the return photons, then it should be possible to retrieve at least part of this "shape" information from the time-signal recorded with a single-pixel detector. By training an artificial neural network (ANN) to recognize the differences between three different individuals hidden behind a wall (using a 1024-pixel SPAD array to parallelize the data acquisition), it was possible to acquire new data with one of the individuals and, from the temporal histogram of just one pixel, to correctly classify both the position and the identity of the hidden person.

As this discussion shows, there are inherent tradeoffs involved between computational power and the complexity of the final output. The complexity can

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range from a full 3-D scene reconstruction, requiring expensive hardware and significant computational effort; to simpler object tracking, cheaper in both hardware and computational effort; to ANNs for object identification, which are cheap in optical hardware but expensive in computational power (although that computation is front-loaded in the ANN training session).

The future around the corner

This feature has focused on the "mainstream" approach to imaging behind walls—that is, on techniques that rely on active illumination of the scene with a pulsed laser and the detection of return signals. Other proposed approaches could find use in specific scenarios, and should be considered in future developments. For example, continuous-wave lasers rather than pulsed lasers might be used, where the object shape is reconstructed from distortions induced by the object in the reflected "glare" observed on the screen, as proposed by Jonathan Klein and colleagues.

The possibility of using speckle patterns and the speckle memory effect in reflection from a scattering surface has also emerged, and recent work from the lab of OSA Fellow Aristide Dogariu of CREOL, University of Central Florida, USA, has suggested looking at signatures in spatial coherence of the signal that is received from behind the wall. This latter approach raises the potential for fully passive sensing that no longer requires any form of illumination and that reconstructs the 3-D scene from shadows and statistical properties of the photons that make the journey from behind the wall to the detector.

Computational imaging techniques and single-photon sensors are rapidly progressing, and the fusion of these two research areas is producing new imaging capabilities—not merely enhancements of conventional imaging, but paradigm-changing ideas in which seemingly impossible feats are performed. There are currently high expectations in the field, with hopes that it will soon produce cameras that can see through opaque media, inside the body and (why not?) also behind walls.

The major challenges to be addressed involve the difficulty in achieving real-time 3-D imaging with a device that is safe for the eyes, portable and easy to use. These are largely engineering problems—although the nature of these is such that systems may need to be completely redesigned or even based on different principles from those currently in use. These challenges are bringing together computer scientists, laser physicists and photon detection experts in the search for a new generation of cameras that can look behind the scenes. OPN

OSA Fellow Daniele Faccio (Daniele.Faccio@glasgow.ac.uk) is with the School of Physics and Astronomy, University of Glasgow, U.K.

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