When the COVID-19 pandemic hit, many regular activities ground to a halt as schools and businesses closed. For some researchers and engineers, however, the pandemic also provided inspiration to take on new problems. Optica Fellow Kimani C. Toussaint Jr., professor and senior associate dean for research and strategic innovations in the school of engineering at Brown University, USA, and his Laboratory for Photonics Research of Bio/nano Environments (PROBE Lab), became particularly intrigued by the inequities in health care that COVID-19 was bringing to the fore.

Pulse oximeters, a key tool in monitoring the status of COVID patients, are less accurate for people with dark skin tones, which could result in their receiving inadequate treatment and oxygen. The PROBE Lab looked to its interdisciplinary research on bio and nanophotonics to find a new solution to this critical issue—work that has garnered significant attention and opened the
door to the possibility of additional health care technologies enabled by optical technology. OPN recently talked with Toussaint to learn more about how he got started, what his lab is working on and where it’s headed.

**Genesis of the PROBE lab**

Toussaint was attracted to science from an early age. Even before he fully grasped his interest in engineering, he knew he liked to take things apart—although he says the reverse operation, putting them back together, was not always as successful. He carried this curiosity with him through college, but he wasn’t sure what he wanted to focus on until he started working closely with a professor who specialized in optics. After many stimulating conversations, Toussaint dove into photonics and hasn’t looked back.

Toussaint’s penchant for interdisciplinary collaboration started early, too. When he first became an assistant professor, his primary focus was in nonlinear optical bioimaging, but he also had some background in nano-optics. He hadn’t seriously considered the latter interest until a colleague asked to use a bioimaging platform he was building to characterize nanotechnology instead. Toussaint realized he could (and wanted to) pursue that area as well. So he started working on nanoplasmonics, applications for optical tweezers, and second-harmonic-generation (SHG) imaging of biological tissues—all on the same platform.

Although he didn’t set out to build an interdisciplinary group, his dislike of “being put in boxes” and his desire to pursue a variety of interesting problems made him a natural collaborator with other scientists. “I knew at some point I was going to integrate the two areas, so I came up with the idea of having a PROBE lab, where we would have both the nano and bio environments,” said Toussaint. “And whether we put a biological system or some type of metallic nanostructure under the microscope would dictate whether we were focusing on the biophotonics or the nano-photonics aspect. In many ways they could use the same tools, and that’s what was really appealing for us.”

**Turning to health care**

Since Toussaint moved to Brown from the University of Illinois at Urbana-Champaign, USA, in 2019, the lab has continued to focus on nonlinear optical imaging and quantitative SHG imaging. But in the wake of the pandemic and in the rich biomedical culture at Brown, the team has started to look at physiological sensing based on optical technology—specifically aiming to make sensing more accurate and equitable.

Pulse oximeters work by using an LED to send light through a patient’s finger and then calculating the relative absorption of light by oxy and deoxyhemoglobin. But melanin also absorbs light, which can cause the instrument to overestimate the amount of oxygen in those with darker skin.

As the problems with pulse oximeters became increasingly acute and obvious, the PROBE team, led by Toussaint and Ph.D. student Rutendo Jakachira, took on the challenge. They’re bringing to bear classical optical methods, usually familiar only to those well-versed in the field, on a practical health care application. The technology that the team is currently developing will use polarized light, which, under the right conditions, could be used to obtain more accurate readings in people of all skin tones and thereby provide better treatment. Jakachira received one of the Optica Foundation’s newly unveiled Amplify Scholarships for her work on the project.

This research has opened new possibilities for applying optical technologies in health care aside from the traditional application of...
microscopy, according to Toussaint. If its pulse-oximeter technique is successful, the team also hopes to leverage optics to look at heart-rate monitoring, contactless body-temperature sensors and other sensing technologies in an effort to make them better and eliminate potential bias.

Toward greater impact

Toussaint says the pandemic has changed his view of what area of his work could have the highest impact, and he now sees the possibility of large-scale societal benefit from the intersection of optics and health care sensing. He has been pleasantly surprised at the amount of traction the lab’s pulse oximeter research has gotten, given that it is fairly old technology.

“We’ve been working on things that are more esoteric,” said Toussaint, “but when your parents or grandparents can understand you’re working on this technology that they use in the hospital—it can really have a big impact, because people get it. We’ve had physicians approach us because of articles they read about our work and offer to collaborate.”

—Kimani Toussaint Jr.

We’ve had physicians approach us because of articles they read about our work and offer to collaborate, which is what we’re doing now.”

This interest in health care research dovetails with the PROBE Lab’s collaboration with CELL-MET, an NSF Engineering Research Center in cellular metamaterials, which has provided another outlet to consider an optics solution for a serious health problem. CELL-MET aims to create cardiac patches capable of repairing damaged hearts and cardiac tissue platforms that can be used for heart physiology and disease research. The PROBE team is applying its optical metrology research to help visualize these artificial heart patches in situ in a label-free fashion.

Reading and writing tissues

In addition to the recent focus on equity in sensing technologies, the lab has continued to push forward in other areas. Optical polarization has long been a passion for team members and a core element of the lab’s work. In the past, Toussaint’s group has combined SHG imaging with polarimetry to look at collag-genous tissues and ascribe metrics associated with Mueller matrices that may correspond to depolarization, retardants or birefringence, for example.

However, since biological tissue systems are very complex, polarization analysis can be difficult to understand—there are many factors that could alter one’s interpretation of the polarization observables. So the team is working on synthesizing tissue phantoms that have varying degrees of cross-linking properties, and doing controlled experiments to determine how changing those properties alters a set of polarization metrics. Such an approach, the researchers believe, would—if successful—make this analysis simpler to understand.

Toussaint notes that the PROBE Lab scientists are fortunate in having easy access to the tissues necessary for their research, but not everyone has such resources. “We’ve been thinking about ways of democratizing this access,” he says. In particular, they can use the information on a biological tissue system captured via SHG imaging to re-create the system using two-photon lithography, and then feed it through a process that validates the copy’s structural information and
biological integrity, to see whether the printed tissue behaves like the original. They envision using machine learning to narrow down and manage the “bookkeeping” of the process parameters.

The final result would be a high-fidelity reproduction of the original tissue sample that the PROBE Lab could then share on an open-source data platform. By going from the “reading” process of using imaging to analyze tissues to a “writing” process that controllably re-creates those tissues, the approach would provide access to such samples to researchers who might not usually have it.

**New perspectives on the fundamentals**

“Just when you think everything’s already been solved, you find out there’s a million things that you don’t know, and that could potentially be done with manipulating optical fields and fundamental properties,” Toussaint says.

For instance, the team is taking a different perspective on the methods it uses to quantitatively model collagenous tissues. Some of the quantification techniques that the team initially developed alongside SHG imaging were limited by tissue complexity. This is problematic, since biologists are interested in understanding how, for example, collagenous structures might change over time or under a particular condition.

To resolve the issue, the PROBE Lab researchers are borrowing tools from computational fluid dynamics. They’ve found that collagen-fiber orientation can be viewed as “pseudo-vector fields” and analyzed using metrics from fluid mechanics. Modeling a sample as a fluid allows collagen architectures to be assessed as part of a unified system, similar to fluid flow, providing new insight into their organization in complex tissues.

The PROBE team is also working with classically entangled fields—optical fields with correlations between at least two non-separable intrinsic degrees of freedom. For example, the spatial and polarization degrees of freedom are classically entangled if their corresponding state vectors can’t be decomposed into a product of the state vectors for space and polarization, as in the case of vector beams.

The team has recently started looking at space-time wave packets, which have correlations between the spatial frequency and temporal frequency and exhibit diffraction-free, dispersion-free and self-healing properties. The group is working to exploit these properties, and even creating a synthesis of both: a space-time vector light sheet to carry out metrology applications.

**A diverse future**

When thinking about the future and exciting developments he’s seeing in his lab, Toussaint points not only to promising health care applications and new possibilities of manipulating optical properties, but also to an increased focus on diversity, equity and inclusion.

In addition to the cross-disciplinary makeup of his group, Toussaint cites its diversity as a major contributor to its success, influencing both the areas the lab has focused on and the way it devises potential solutions to problems. The PROBE lab is at least 50% women and 50% underrepresented groups, and the diversity of perspective and thought that its varied members bring to the table have been instrumental in finding new approaches.

“In general, just really thinking about how diversity and inclusion impact how we work, what we work on and the perspectives that we bring to the fore when it comes to solving problems—that’s been very illuminating,” says Toussaint, “I think more people are realizing the power behind that, and that’s awesome.”

Hannah Lanford is the managing editor of OPN.