Out of this World Technology: The NASA Smart Probe

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Technology developed by the space program may soon improve neurosurgeons' ability to identify brain tumors. This robotic apparatus permits finer control than is possible with the human hand. But this robot is not merely a precision tool for improved localization: it contains a "smart" probe that actually learns from experience.

An interesting origin

The smart probe's origin is an unlikely source: geological surveys. Dr. Robert W. Mah, Principal Investigator of the Smart Systems Research Group at NASA Ames Research Center, had been working on a probe that could analyze planetary terrain. Equipped with an array of sensors, the probe would analyze a sample and compare those results to information stored in databases. From there, a reasonable estimate could be made concerning the sample's composition.

Dr. Russell J. Andrews, Chief of the Division of Neurosurgery at Texas Tech University Health Sciences Center and Ames Associate, NASA Ames Research Center, and Dr. Mah met in 1992 to discuss the common challenges between neurosurgery and soil analysis. Although these may initially seem quite disparate techniques, the researchers realized both procedures would benefit from (a) improved accuracy for probe placement, and (b) better ways to analyze the target region.

Limitations of current surgery

There are presently two major limitations in brain tumor surgery. First, preoperative imaging techniques such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are currently used to guide the surgeon in brain tumor surgery. However, such surgery uses a handheld probe, relying on tactile feedback to the surgeon's hand. An inadvertent nick of a blood vessel while negotiating brain tissue could lead to hemorrhage and result in a stroke.

A second limitation is that either the brain or the tumor may change position during an operation, rendering the preoperative scans invalid. Drs. Mah and

Andrews reasoned that a probe with different sensors on its tip would avoid both problems and also convey information about the tumor in real-time, rather than waiting days for a pathology report.

While CT/MRI can provide a tumor's general localization, it is imprecise. In contrast, the smart probe examines the local environment using various modalities, thereby increasing the confidence in identifying the brain region. Dr. Andrews said "We know we must be in a certain part of a brain because no other area has these exact characteristics. It's analogous to flying to London: the global positioning system (GPS) will get you to Heathrow airport, but if details have changed, say a terrorist attack has eliminated a runway, there's no way the GPS will know that. The pre-operative imaging systems are similar to a GPS, in that details could change and you'd be unaware of it because you're not using real-time information."

Both researchers felt the present methods to guide probes to tumors were clearly suboptimal. Ultrasound is one method to guide the biopsy needle to a lump in the breast. However, Dr. Mah noted that "Most of the valuable data collected by the ultrasound technique remains unused. For example, if the tumor is spiculated (i.e., has spikey edges), it could metastasize. The tumor's size and degree of concavity/convexity are also informative." Clearly, a probe that could convey information, rather than merely extract tissue, would be preferable.

Multimodal Sensors

The investigators thought that not only should the probe convey information, but that data should be of various types. According to Dr. Andrews, "By having an array of multimodal sensors, we gain a higher degree of confidence in diagnosing the tumor as malignant or benign. Your diagnostic ability is limited with a single modality. For example, ultrasound is normally useful, but it is severely limited if it encounters a lot of blood. You really need 99 percent certainty in surgery; you can't get by on 85 percent. But if you had many sensors each of which was 85 to 90 percent accurate and if these all are correlated by the computer software, you could be very certain that what you're seeing is a particular type of tissue."

The smart probe is a marvel of such cutting-edge technologies as robotics, neural networks, and microsensors of various types. At the heart of the probe is a 6000-pixels fiber optic camera. A strain gauge measures tissue stiffness (tumor tissue is typically stiffer than normal tissue). Another sensor measures the partial pressure of oxygen (malignant cancer has low oxygen levels). There are also microsensors for pH, electrical activity, various chemicals, and blood flow.

The fiber optics also shed light—literally and figuratively—on the tissue at the probe's tip. The reflected light is a unique signature, depending on the chemicals in the tissue. Dr. Mah noted "At different wavelengths, you get a waveform that reflects certain tissue types. We compare the parameters in one waveform to another waveform, and that's how we teach the software to distinguish tissue types."

The words "learning software" generally evoke images of software that instructs, whether it's a Sesame Street counting program or a Visual Basic CBT (Computer Based Training program). However, we've now fully entered the era where the software can actually do the learning. The smart probe achieves this by taking the multiple sensor inputs and learning associations with neural net software (see SIDEBAR).

The smart probe on trial

Originally trained on tofu because of its similarity consistency to brain tissue, the smart probe is ready to change its "diet." Dr. Mah noted "We're in the middle of animal trials now, measuring normal characteristics in muscle, fat, kidney, and spleen in different parts of the brain. Fortunately, the sensor signatures we get of these different types of tissues are quite different, which is important."

The researchers are not limiting their investigations to normal non-human tissue. "We're growing human mammary tumors on the backs of rats and measuring these with the probe to distinguish cancerous from normal tissue," said Dr. Mah. "FDA-approved human trials for brain biopsy may start mid-year," noted Dr. Andrews.

Future trends

The smart probe and its analysis techniques could be used to monitor biomedical research in space, such as the effects of weightlessness. Several "next generation" surgical tools, having more sensors and real-time diagnostic capability, are already under development.

While other investigators have used a single-modality probe to distinguish abnormal from normal tissue, the technology hasn't reached the point where it can be clinically useful. This is partly because the analysis must be performed under ideal conditions. In contrast, Dr. Andrews noted that "NASA's thrust is to continue to use the neural net software to analyze and integrate data from a probe with multimodal sensors. We intend to do this with a robust probe that would be reliable and an operating room where you have blood, abnormal lighting, and other nonstandard conditions."

This space-age technology won't remain earthbound. A long term goal is to have the probe as part of a "robotic astrosurgeon" on board the two-year Mars mission planned for 2020. It is conceivable that the astronauts would have pre-launch CT or MRI scans in a data bank for baseline. During the mission, automated robot tools could analyze tissues with the smart probe and compare the real-time values with the baseline measures. The surgeon, perhaps on Earth, could issue high-level commands to the robot and perform additional diagnostic or surgical procedures.

Dr. Andrews said "It may sound very much like *Star Trek*, but much of the technology is already here separately--it just needs to be integrated. There's already an FDA-approved robot for neurosurgical procedures. Today you could be in Maine and perform an operation in Iceland. With a patient in a stereotactic frame, you would use the smart probe to confirm location by comparing real-time measures with CT database values. The probe sensors could indicate the type of tissue, and you could decide whether to excise it with a laser, for example. It's actually very feasible today, whereas 30 years ago it was impossible because CT, MRI, neural net software, and robotics didn't exist.

"It will happen; it's just a question of how fast."

SIDEBAR: "Neural Nets 101"

Although a neural net discussion could fill this magazine and probably the room in which you're reading it, the underlying theory is not difficult. In essence, the smart probe's neural net software loosely models the neurons in brain and their interconnections. This logic permits analysis of aggregated sensor parameters, allowing the software to "learn" to distinguish various tissues.

Dr. Mah explains, "Just as the brain can be modeled by a series of interconnecting neurons, you can assign a 'weight' to each of those and make a mathematical model. The input to the neural net are any impulses that pass through those neurons, which get multiplied by that weight. The output could be as simple as one or two neurons."

Dr. Mah elaborates, "In practice, you insert the probe into a known tumor. The various sensor data are the inputs, which you use to teach the neural net to generate a 'malignant' output. The learning aspect is that the weights of the various sensors get adjusted. This happens in a fraction of a second, which is important: as we insert the probe into the brain going toward the tumor, we first learn what's normal for the patient. Our software must learn a patient's normal properties before the probe makes contact with the tumor. The software creates a confidence interval around those various sensor values. When that interval is exceeded, the tissue at the probe's tip is deemed abnormal (i.e., cancerous). That's one way to try to define the edges of the tumor."

Dr. Andrews noted that the neural net software can compare an individual's readings to a population, and can also compare differences within a patient. If your patient differs from the population readings, you can either add this patient to the database as a normal variant, or note her as an abnormality.

Neural nets are not limited to oncology, noted Dr. Andrews. "EEGs and EKGs are also being analyzed by neural nets to identify abnormalities. It’s basically the same as in our smart probe procedure: a database of various normal values is assembled and the patient’s values are compared with those in the database."

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