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Engineering control theory helps create dynamic brain models

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Models of the human brain, patterned on engineering control theory, may some day help researchers control such neurological diseases as epilepsy, Parkinson's and migraines, according to a Penn State researcher who is using mathematical models of neuron networks from which more complex brain models emerge.

"The dual concepts of observability and controlability have been considered one of the most important developments in mathematics of the 20th century," said Steven J. Schiff, the Brush Chair Professor of Engineering and director of the Penn State Center for Neural Engineering. "Observability and controlability theorems essentially state that if you can observe and reconstruct a system's variables, you may be able to optimally control it. Incredibly, these theoretical concepts have been largely absent in the observation and control of complex biological systems."

Those engineering concepts were originally designed for simple linear phenomena, but were later revised to apply to non-linear systems. Such things as robotic navigation, automated aircraft landings, climate models and the human brain all require non-linear models and methods.

"If you want to observe anything that is at all complicated—having more than one part—in nature, you typically only observe one of the parts or a small subset of the many parts," said Schiff, who is also professor of neurosurgery, engineering science and mechanics, and physics, and a faculty member of the Huck Institutes of the Life Sciences. "The best way of doing that is make a model. Not a replica, but a mathematical representation that uses strategies to reconstruct from measurements of one part to the many that we cannot observe."

This type of model-based observability makes it possible today to create weather predictions of unprecedented accuracy and to automatically land an airliner without pilot intervention.

"Brains are much harder than the weather," said Schiff. "In comparison, the weather is a breeze."

There are seven equations that govern weather, but the number of equations for the brain is uncountable, according to Schiff. One of the problems with modeling the brain is that neural networks in the brain are not connected from neighbor to neighbor. Too many pathways exist.

"We make and we have been making models of the brain's networks for 60 years," Schiff said at the recent annual meeting of the American Association for the Advancement of Science in Boston. "We do that for small pieces of the brain. How retina takes in an image and how the brain decodes that image, or how we generate simple movements are examples of how we try now to embody the equations of motion of those limited pieces. But we never used the control engineer's trick of fusing those models with our measurements from the brain. This is the key—a good model will synchronize with the system it is coupled to."

Schiff is looking for the models that represent the parts of the brain he is studying. He looks at the model to see if it can simulate what he observed and if he can fuse the model with the real system. He and his colleagues, with support from the National Institutes of Health, are exploring a wide range of control strategies for epilepsy, Parkinson's disease and migraines.

To do this with brain networks, researchers often have to measure from only one or a few nodes of the system and seek to reconstruct the rest.

"We need to simplify, and then ask, how far into that network can we reconstruct?" asks Schiff. "How far can we control?"

Using group theory, Schiff is trying to answer these questions. Group theory tests whether the inputs onto these nodes can be swapped. If a regular swap of the nodes ends up with the same network, then this is a symmetry of the network. Such symmetries underlie powerful ways to simplify models that represent the underlying structure within brain networks. The brain is full of such symmetries as neurons hook themselves up in rings and star patterns.

"But 10 billion neurons produce a number of possible networks that no one wants to think about," said Schiff. "Luckily, in the brain, internet or power grid we can begin to take symmetries into account. We don't need to go and specify all the particulars about how things are connected, but take advantage of the underlying symmetries in those networks and produce representative networks."

In essence, complicated networks can be boiled down to the simpler networks that represent what the complicated ones do. Brain symmetry permits synchrony to arise, and this is critical since synchronies are so important to both the normal and abnormal function of brain networks.

Recording from just one electrode from the brain is very limiting. Researchers and clinicians now use arrays of 100 or more electrodes to study epilepsy, but technology will soon provide the capability of deploying a 1,000 or more electrodes that, when fused with models, will enable us to reconstruct activity more deeply into the nervous system.

"The pathologies of epilepsy or Parkinson's disease, we think are very 'simple,' compared with many more complex activities we perform in our brains, " said Schiff. "If they have more synchrony than normal they might produce really good reconstructions when fused with models."

These simplified models are important not just for these specific diseases, but because a fidelity model of the brain, one that models everything in detail, would be impossible to create. In addition, such large-scale models would be very inaccurate if used in such a control-engineering framework. If Parkinson's disease, epilepsy or migraines can be modeled more simply and still be accurate, then other brain pathologies or functions might also be modeled and controlled with simplified models.

The mechanism underneath migraine headaches is a very slow wave that propagates through the brain cortex. Schiff is using these engineering principles to model this wave. He and his colleagues are using these principles to do real time control of this wave phenomenon in brain.

"It is a very exciting time as we see the results of fusing these engineering and mathematical principles with observing and treating the brain," said Schiff who is the author of Neural Control Engineering: The Emerging Intersection between Control Theory and Neuroscience.

Provided by Pennsylvania State University

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