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Researcher seeks to tame 'ghost' of uncertainty in complex dynamic systems

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We're surrounded by dynamic systems—systems demonstrating behavior changing through time—in engineering, nature, civilization, even our personal lives. Even an ordinary bathtub could be considered a dynamic system with inflow and outflow of water and a reservoir level in the tub (along with a few rubber ducks, maybe). More complex dynamic systems include aircrafts, robots, glaciers, traffic flows, power grids, national economies and global climate change.

Predicting behavior of complex systems in civilian, military and scientific fields always has been plagued by uncertainties that are vexing to model. So, developing accurate predictive mathematical equations and algorithms dealing with such systems depends on accounting for "unstructured uncertainty."

Back to the bathtub example, forecasting a possible water overflow during a bath is made more difficult due to unstructured uncertainties such as un-modeled dynamics (drain clogs), external disturbances (cats), inherent variabilities of the dynamic processes (movements of random bathers), sensor noise (water level gauge isn't 100 percent accurate) and data transmission errors (the Wi-Fi is down).

Now, a major cooperative research agreement with the U.S. Army Research Laboratory (ARL) is supporting work at the University of Kansas School of Engineering to develop a foundational mathematical framework and effective approaches for state estimation for complex dynamic systems with uncertainties.

"Dynamic systems are central to contemporary society," said Huazhen Fang, assistant professor of mechanical engineering at KU, who is leading the research. "We want to capture the behavior and phenomena of a system using mathematical models. But models aren't perfect because there are so many uncertainties, like modeling errors or external disturbances or intrinsic variability that affects the dynamic process."

Fang's work will focus on developing formulas—or mathematical models and algorithms—that account for the "ghost" of unstructured uncertainty, then using them to analyze, monitor, predict or control the system's behavior.

"We use probabilistic methods," said the KU researcher. "We try to identify the probability-based appearance of uncertainties conditioned on the data. This will lead us to develop mathematical models and efficient algorithms that can effectively account for the ghost presence of uncertainty. That seems impossible but we can find a way. Our ideas were reinforced by some quite promising preliminary results."

"Understanding the behavior of complex dynamic systems is an integral part of many critical defense systems enabling robust manned-unmanned teaming, state awareness, risk assessment, flight control, etc.," said Mulugeta Haile, team leader in the Vehicle Technology Directorate of the ARL. "The cooperative research with KU will address some of the fundamental challenges in these areas."

Fang's research plan includes a holistic investigation, which not only concerns predicting a system's behavior despite uncertainties but also studies sensor-based observation structure to obtain high-quality data beneficial for prediction. To explain the need for data from well-placed sensors in a dynamic system, Fang described how to predict and estimate the temperature in a tall glass skyscraper, another dynamic system with unstructured uncertainty.

"The change of temperature in a building can be disturbed by the sunshine or a cloud," he said. "The uncertainties are very difficult to capture in a dynamic model. If we look at a building's temperature, the distribution isn't even. We want to monitor the temperature throughout the building, so we must use sensors. The placement will be critical. We must find a smart way to place sensors to get informative data. We couldn't place them all in one location—that would be stupid. But if we can invent a way to place sensors according to the temperature dynamics, the data quality will be significantly enhanced."

Fang said his project could have many applications to the military, such as enabling more robust autonomy, navigation, guidance, target tracking, sensor fusion, fault detection and structural health prognostics. Further, he said the basic research supported by the new ARL grant could power consumer products like GPS navigation by improving on an already used algorithm to deal with uncertainty called the Kalman filter.

"Certainly, in navigation, there can be uncertainties," Fang said. "If GPS signals can be disturbed or attenuated by different sources like magnetic storms or tall buildings in an urban area like Chicago, GPS will not work very well. How do you overcome this? The Kalman filter in GPS provides less accurate estimation because of these uncertainties."

Fang will carry out the work with collaborators in the ARL for the next three years.

"We want to transition algorithms to address many real-world problems, to maximize the full potential and benefits of the fundamental research proposed in the project," he said. "It will produce practical and useful algorithms, which are likely to find prospective use in different applications for people everywhere."

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