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Solving the Unsolvable

For his pioneering development of a mathematical theory that has enabled solutions for previously intractable problems, UC Santa Barbara's Igor Mezić has received the biennial J. D. Crawford Prize from the Society for Industrial and Applied Mathematics (SIAM) Activity Group on Dynamical Systems (SIAG/DS).

Established in 2000, the Crawford Prize recognizes contributions from a paper addressing fundamental issues in the dynamical-systems field. The awarded work by Mezić, a professor in the Department of Mechanical Engineering and in the Department of Mathematics, innovates on the 90-year-old Koopman Operator Theory.

His single-author 2019 paper, "Spectrum of the Koopman Operator, Spectral Expansions in Functional Spaces, and State-Space Geometry," in the journal Nonlinear Science, presented a mathematical theory that made it easier to understand and speed up an array of formerly unsolvable computations in applications including fluid dynamics, energy-efficient design, network security and operations, and complex systems dynamics.

"We offer our congratulations to Igor Mezić for the tremendous recognition and prestige that come with the Crawford Prize," said Rod Alferness, dean of the UCSB College of Engineering (CoE). "SIAM is a top professional group in the world for dynamical systems research. It is exciting to see Igor receive this award for his innovative work, which has pushed Koopman operator theory forward and broadened its use in applications ranging from power-grid operations to

neuroscience.”

“It’s wonderful to me that the dynamical systems community deems my work worthy of the Crawford Prize,” said Mezić, also the director of UCSB’s Center for Energy Efficient Design and head of the Buildings and Design Solutions Group at the CoE’s Institute for Energy Efficiency. “The depth and breadth of dynamical systems research is immense, and much of it is of top technical quality and has broad impact in engineering and the sciences. The value of the prize is heightened for me just by the sheer quality and volume of the competition for it.”

The award’s namesake, John David Crawford, who died in 1997, conducted groundbreaking research in which he recognized the inherently chaotic dynamics that occur inside plasma and cause particles to escape whatever mechanism is used to contain them. Mezić offers a user-friendly allusion to the chaos theory inherent in Crawford’s findings, recalling Jeff Goldblum’s character in the film “Jurassic Park,” who said, prophetically, “Life will not be contained. Life breaks free.”

Crawford made seminal contributions to using geometric data-science tools to model chaotic systems, Mezić noted. “Those tools provide precise answers in systems that have relatively few dimensions,” he said, “but a system having more than three dimensions, such as an automobile, which might get a hundred pieces of data from a range of dynamic systems indicating gearbox status, speed, torque, etc., is very hard to represent geometrically.”

Mezić realized that a different mathematical framework was needed to model such complex systems. He first began working on the problem for his Ph.D., which he received in 1994, by incorporating Koopman. The theory had been developed in the 1930s but was never used on a large scale because the geometric point of view was so popular. Mezić, however, realized it could be useful.

“I wanted to preserve the power to describe geometrical objects — because humans think geometrically — but work it so that you could understand a dynamical system that has many dimensions,” he said. “I’ve ported geometric concepts of dynamical systems into an operator theoretical context so that they can be turned into algorithms, artificial intelligence, etc. It is adding to geometry that Crawford utilized by setting them up in a different, more easily utilized domain.”

Whereas a car has a hundred or a thousand dimensions to its dynamical system, artificial intelligence and deep-learning systems have hundreds of thousands or even

millions of dimensions. Mezić's theory not only has the mathematical power to resolve such complex systems, but also avoids abstraction, he said, so that "it is very cleanly and clearly understandable what the objects are."

The most important contribution of his work on Koopman operator theory, in his own words, is that it "basically opens your mind to be able to think in larger dimensions using intuition from lower dimension. I often think about the fact that there are elements of applied math and engineering that are highly conceptual, and if you are very good technically — and you need to be — you can manipulate symbols and get a result." But Mezić has always been interested in using math to distill the concepts beyond abstract symbols and equations.

His theory did not come into immediate use. It was the focus of his plenary session talk at the 2009 SIAM meeting in Snowbird, Utah. But, as he explained, people have a finite amount of time to dig into complex new tools and tend not to do so until they encounter a problem where the tool might be useful, at which point they commit to understanding it.

A decade after Mezić's plenary talk, use of the theory has snowballed, he said. Application in such areas as fluid mechanics, power grid operations and energy efficiency in buildings, soft robotics and neuroscience have demonstrated that "it can be effectively applied to say something useful to society."

"The thing that excites me most about Mezić's work is the emerging ability it provides to tackle perennially difficult technical challenges," said Matthew Munson, program manager for fluid dynamics at the DEVCOM ARL Army Research Office. "The future Army will operate in an environment that is hugely complex and uncertain, which requires the ability to solve hard problems quickly. The theoretical frameworks and computational tools that Mezić and his team have developed, along with his continuing discoveries, are poised to make a major impact on how the Army solves these future challenges.

"This new approach will change the world," Munson added. "In the future, I think it will be the standard theory used for analysis and prediction of many dynamic systems. The potential applications are numerous, and the potential impacts are enormous."

Support for Mezić's prize-winning paper was provided, in large part, by the U.S. Army Combat Capabilities Development Command Army Research Laboratory (DEVCOM

ARL) via the Multi-Disciplinary University Research Initiative (MURI) program.

Mezić has previously won numerous prizes for his research, among them the Alfred P. Sloan Fellowship in Mathematics, a National Science Foundation CAREER Award, and the George S. Axelby Outstanding Paper Award on "Control of Mixing" from IEEE. He also won the 2007 United Technologies Senior Vice President for Science and Technology Special Achievement Prize for his contribution to a variety of engineering technologies.

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