Researcher seeks to predict and optimize complex engineering systems under extreme uncertainty

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MIT Department of Mechanical Engineering Assistant Professor Themistoklis Sapsis Credit: David Sella

Creating anything new requires testing the limits of what already exists and delving into uncertainty. This is what Themistoklis Sapsis does regularly. "My work is on systems for which we understand as much as we don't understand," the assistant professor of mechanical engineering and director of the Stochastic Analysis and Nonlinear Dynamics Lab says. By using analytical and computational methods, Sapsis tries to predict and optimize behavior, particularly when the dynamics and excitations are uncertain and occasionally extreme. This places much of his work in the ocean environment, and whether it's an energy-harvesting configuration or an ocean structure, his goal is to create designs that maintain operational robustness and safety regardless of the constantly varying conditions.

Designing a better boat

A typical example of Sapsis' work is analyzing the behavior of a ship in extreme weather. It's a system and environment that combines nonlinear dynamics and uncertainty. The latter is caused by the broad range of possible conditions that a ship can encounter and results in the greatest range of possible outcomes that run from benign to catastrophic, he says. The former is an element that's often overlooked but essential for the realistic description of the ship's behavior. By studying them together, the potential increases for being able to produce a better structure. However, the computational cost of such analysis is often prohibitive even with modern capabilities, Sapsis says.

In ship design, there are certain known factors, such as dimensions and hull geometry. There are also less predictable elements, such as the intensity of water crashing into the front and sides. Add to that the possibility of extreme weather. It's not a regular occurrence, but it will happen, and when it does, a ship needs to be able to perform reliably. What's needed, Sapsis says, is the development of new mathematical methods that will be able to define the envelope of safe operations, taking into account even rare events. In order to achieve such a goal, one has to focus on the statistics of the response, which indirectly describe all possible scenarios, rather than the isolated analysis of every possible outcome, which would be prohibitively expensive, he says.

Along with the advantage of taking into account even rare events, Sapsis' approach brings other advantages. He focuses on developing algorithms inexpensive enough so they can run off of a laptop, rather than a cluster of computers, keeping costs to a minimum. That freedom and flexibility lead to a more efficient and safe design. "It means less cost, higher speed and higher reliability," Sapsis says.

Taking motion, making power

Sapsis also works on energy harvesting, particularly as it relates to powering small electronic devices. The same challenges apply as with a ship in the ocean: He looks at an excitation that varies in its occurrence and intensity. Using nonlinear configurations in this realm allows him to not rely on the energy content of a specific frequency, giving a broader range of resonances, he says.

Through a "carefully designed oscillator," Sapsis says that his group is looking to capture energy from walking, walking quickly, and running. These three motions have completely different characteristics, and a traditional approach relying on linear oscillators would require a separate set of design parameters for each case. Using nonlinear mechanical oscillators capable of adaptively resonating with the different paces, kinetic energy would be absorbed and transformed into electromagnetic energy with a robust level of efficiency, ultimately extending the cell battery's life, he says.

The challenge, much like with dealing with ocean waves, is in the characteristics of the excitation. Kinetic energy doesn't always efficiently covert into usable energy. Because different people produce different accelerations when they move, Sapsis says that his design goal is fairly simple: to create consistency and maintain robustness. To do that, he needs a model, and he's chosen a ubiquitous one. "We are inspired by what nature does," Sapsis says, noting that turbulence, found in atmospheric and oceanic flows, is an example of robust energy transfer from scale-to-scale that he's trying to mimic in mechanical settings.

The need for some pushing

Like many of his MIT colleagues, Sapsis work applies to a range of industries: design of ships and offshore structures, reliability of communication and power networks, energy harvesting, and vibration mitigation. The one consistent element is the need for collaboration. Sapsis says that while academia and industry are inclined to have an initial mutual reticence, there are benefits from both sides moving closer to each other. Academia can explore issues that aren't merely theoretical or niche-based but address a larger market need, and industry gets to train the next generation of engineers.

Sapsis adds that more than merely co-existing, there's a greater opportunity to be taken. The two realms need to brainstorm common-interest problems and push themselves to explore issues that aren't usually touched upon, especially ones that incorporate the uncertainty factor into design principles. Doing that will both produce stronger results for a given project and ingrain a mentality and higher expectations for future work. "We have to go beyond the low hanging fruit," Sapsis says.

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