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# Nonlinear Sensing

The past three decades have seen an explosion of ideas in the general field of nonlinear dynamics. In fact, it has become increasingly clear that areas as diverse as signal processing, lasers, molecular motors, and biomedical anomalies have a common underlying thread: the dynamics that underpin these systems are inherently nonlinear. Yet, while there has been significant progress in the theory of nonlinear phenomena under an assortment of system boundary conditions and preparations, there exist comparatively few measurement and instrumentation devices that actually take this rich behavior into account.

In the presence of background noise (a given, for most practical applications), the underlying dynamic phenomena become even richer, with the noise actually mediating cooperative behavior that, when properly understood, can lead to significant performance enhancements and, by inference, improved measurement ability. A striking example of this behavior occurs, for example, when the underlying dynamics undergoes a bifurcation from static to oscillating behavior when a control parameter is swept through a critical value. If properly understood, theoretically, the (suitably quantified) system response can be significantly enhanced near the onset of the bifurcation. Examples of this behavior have been observed in a slew of laboratory experiments on measurement systems ranging from vibrating PET ribbons, to SQUIDs, and, further, this behavior has been hypothesized to account for some of the more striking information processing properties of biological neurons. In many cases, background noise can mediate this behavior, thereby playing a significant role in the optimization of the response of these systems to small external perturbations. This means that noise can actually help the measurement process.

The (by now, well-studied) Stochastic Resonance effect is one example of an underlying phenomenon that pervades noisy nonlinear dynamic systems. The system response can be (somewhat counterintuitively) improved through a delicate tuning of the system parameters; the resulting behavior (that has been exploited in several devices for measurement and instrumentation applications to date) occurs in a very narrow parameter regime, hence a very good understanding of the system response is critical before exploiting this behavior.

Despite the large amount of research and development in the physics of nonlinear dynamical systems, there have been very few engineering applications or realizations to date. A part of this is due to an underlying "culture of linearity": knowing that linear systems are often optimal performers, the tendency has been to operate nonlinear systems in a quasi-linear regime wherein the response may, in fact, be the best that is possible, but only under optimal operating conditions. Under the appropriate conditions, this might be sufficient for some measurements (particularly when the signal amplitude is not too weak). Given the fact that such conditions are rarely met in practice, it would make sense to attempt to exploit the full range of (usually nonlinear) behavior of a system.

In this important aspect, this special issue of *Instrumentation & Measurement Magazine* is very significant: it affords examples of work carried out by non-traditional, forward-looking and innovative researchers, who are not content to understand and exploit the behavior of a nonlinear dynamic system in only a very narrow parameter regime. Operating sensors in their (natural) nonlinear regime leads to enhanced signal detection performance, and higher bandwidth (e.g., in nonlinear energy harvesters), among other benefits. Hence, these conditions are often optimal when issues like SNR, bandwidth, information transfer, etc. are relevant to the measurement application. It is most important, however, to bear in mind an important caveat: a sensor that is underpinned by linear dynamics (through construction or the underlying physics) at the outset, *cannot* be improved by forcing it to operate in a "nonlinear mode." Hence, this special issue is devoted to measurement and instrumentation involving intrinsically nonlinear devices.

This special issue of the *Magazine* provides an overview of just a few of the nonlinear sensors that are being researched and developed, such as:

- A single-core fluxgate magnetometer that is operated in a biomimetic manner: it processes signals via a "rate code," rather than a FFT. The sensor is used to scan for the iron content in the brain; this can provide a marker for neurodegenerative diseases. As a room temperature device costing about $200, this provides a viable/portable alternative to hospital scanning equipment, for certain biomedical scanning applications.

- A description of the "Injection Locking" technique as applied to systems that are nonlinear and have spontaneous oscillations (usually past a critical point). This frequency can be calculated via bifurcation theory, or it can be measured experimentally. Then, applying a locking signal (at precisely the frequency of the spontaneous oscillations) leads to an immediate lowering of the noise floor, particularly at low frequencies where most magnetic detection of weak signals is carried out. A low-frequency target signal that might, otherwise, be buried in the noise floor then becomes visible.
- A bio-inspired image sensor that, functionally, mimics the retina in vertebrates. The authors state: "We expect that by placing our simulator in the hands of interdisciplinary researchers, especially computational neuroscientists, mathematical scientists and machine learning practitioners, it will foster the development of more efficient representations of visual inputs in deep learning applications."
- A tunable strain sensor whose nonlinear response is exploited to enhance its sensitivity under a given set of operating conditions. When properly configured, the sensitivity greatly exceeds that of conventional strain sensors. The sensor exploits the piezoresistive behavior of MoS2 (Molybdenum Disulfide); this is the semiconductor material that underpins the sensor.
- A nonlinear energy harvester that uses the response of a flexible PET ribbon to harvest energy from vibrations. The ribbon operates as a bistable switching device. The paper includes a second-order behavioral model of the underlying dynamics with a nonlinear restoring force. The power produced is sufficient to transmit a wireless signal to a transceiver placed at about 30 feet of separation.

One hope is that a reading of this special issue will inspire researchers to open their minds and explore far beyond the "textbook" boundaries that all-too-often circumscribe the thinking of young scientist/engineers.