

Taking Sensor Simulations to New Frontiers: The COMSOL Perspective

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Summary:

Modeling and simulation have become major drivers of sensor design and innovation. What began with multiphysics coupling has evolved into a broader ecosystem that now includes optimization, uncertainty quantification, surrogate modeling, simulation apps, digital twins, and large language models.

Keywords: Modeling, Simulation, Multiphysics, Surrogate

Introduction

Sensors are inherently multiphysics devices. Translating a physical phenomenon (such as the concentration of a biomarker) into a measurable signal (often electrical) involves multiple interacting domains, including fluidics, optics, and electrochemistry. These interactions are typically described through coupled balance equations for mass, momentum, energy, and charge, or through fundamental frameworks such as Maxwell's or Schrödinger's equations. The resulting couplings may arise from mutual loads or complex material behavior.

To capture that complexity, modeling and simulation have become commonplace in academic and industrial research, helping to better understand sensor systems, refine their response, and inspire numerous innovative methods and designs. Thanks to its rigorous Multiphysics concept and homogeneous architecture, COMSOL Multiphysics® software [1] has been a key driver of innovation in the sensor community for more than 30 years.

A typical multiphysics model for a sensor, incorporating several coupled partial or ordinary differential equations, is often just the starting point. In practice, these models are increasingly embedded in larger algorithmic structures, such as parametric sweeps, optimization, sensitivity analysis, uncertainty quantification (UQ), model order reduction (MOR) and data analysis, as well as interactive platforms for different classes of users (simulation apps).

These new frontiers reflect the insatiable desire for more performance and more ease. Conquering them involves the integration of the key technologies of our days into simulation algorithms: scalable hardware in clouds and on GPUs,

machine learning (ML) as well as large language models (LLM) and other AI concepts.

Optimization

The ultimate goal of simulation-driven sensor design is no longer just to predict a response but also to optimize design and operational parameters, including dimensions, materials, and control functions.

With the COMSOL Optimization Module, scientists and engineers can use a range of gradient-based and gradient-free optimization algorithms with the same ease of use as when selecting PDEs for physics. In parameter optimization, a set of inputs serves as the control, whereas shape optimization allows the parametrization of smooth surfaces defined by polynomials. In topology optimization, a material density function serves as the control variable, enabling unexpected, generic designs that can also incorporate manufacturing constraints. The latest innovations include time-dependent optimizers for optimal control and global optimization (EGO Solver), as well as Design of Experiments (DoE) and surrogate modeling.

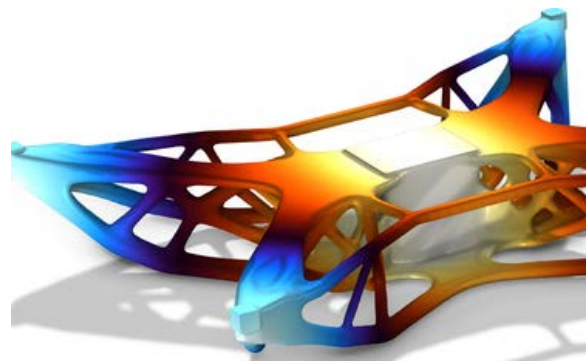


Fig. 1. Topology optimization of a drone.

Uncertainty quantification

The objective function for sensor optimization may include several quantities of interest: sensitivity, size, cost, and robustness. To extract measures of robustness, we need to account for the fact that all input parameters in a design are subject to statistical distributions, and consequently, so is sensor performance.

The COMSOL Uncertainty Quantification Module effectively evaluates model assumptions, simplifies models, identifies key inputs for the quantities of interest, explores their probability distributions, assesses design reliability, and calibrates unknown input parameter distributions. Confirming model accuracy and gaining a better understanding of the quantities of interest help reduce costs in production, development, and manufacturing.

Such analyses cannot rely solely on Monte Carlo-type calls to sensor simulations because complex multiphysics models can be computationally expensive and preclude brute-force mapping of a multidimensional parameter space. To advance, recent COMSOL releases make use of Latin Hypercube sampling (LHS) and, again, surrogate modeling, specifically Gaussian processes (GP) or polynomial chaos expansion (PCE).

Surrogate modeling

Surrogate models approximate the results of full finite element models. They are generally simpler, more compact, and require fewer computational resources than the full models. The path to obtaining a surrogate model typically involves two steps: data generation and training. During data generation, a DoE algorithm, e.g., one based on LHS, effectively maps the parameter space and produces a comprehensive design table. Each row contains a set of input parameters and corresponding outputs. In a training session, the design table is used to train a suitable surrogate (e.g., DNN, GP, or PCE). The surrogate model can then be called as a (fully differentiable) function, providing an approximate response for the sensor instantly. Typical use cases include fast optimization, uncertainty quantification, instantaneously responsive simulation apps, and digital twins.

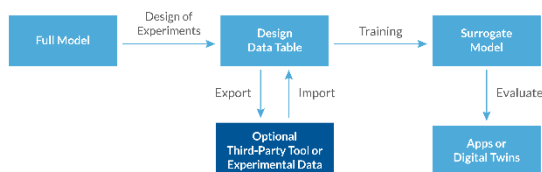


Fig. 2. Workflow of surrogate model design, training, and use. Optionally, measured data can be included. Surrogate models can also be exported.

Simulation Apps and Digital Twins

Simulation apps in COMSOL make sensor simulations accessible to lab technicians, managers, physicians, customers, and patients. Physics-based models include GUIs for safe use by non-experts and can connect with instruments, databases, and external codes.

Apps can be deployed in two ways: With COMSOL Compiler® apps can be compiled into royalty-free, standalone software for Windows, Linux, or macOS, which users can distribute either free of charge or for sale. Alternatively, a web server-based solution, COMSOL Server®, can host apps that are readily accessible from any web browser, including those on tablets and smartphones.

With server-side computation and the integration of surrogate models, these apps can deliver near real-time results. This capability is particularly important for digital twins, where live data from physical systems continuously updates and refines the virtual model, enabling predictive monitoring and improved decision-making.

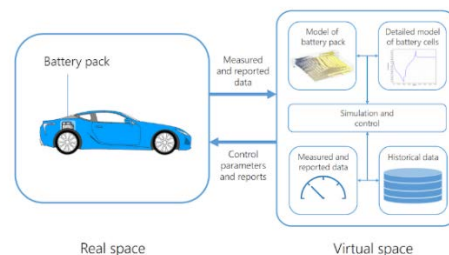


Fig. 3. Concept of an interaction of a battery pack in a real car and its digital twin in the virtual space.

Chatbot integration

State-of-the-art simulation tools are increasingly integrating large language models into their architecture. In COMSOL, users can integrate their OpenAI-compatible chatbot of choice to assist with modeling, generate code that can be executed directly, or saved in powerful methods. Thanks to the uniform object-oriented software architecture, it is already possible to build simple educational PDE models solely through prompting. Sharing models with chatbots makes bug checking straightforward, even for more complex models. Future versions are expected to expand interoperability with LLMs.

Conclusion: Sensor simulations today go far beyond physics and significantly accelerate the workflows of engineers and scientists by integration of cutting-edge algorithmic innovations.

References

- [1] COMSOL Multiphysics® v. 6.4. www.comsol.com
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