

Accelerated Design and Characterization of Inductive Position Sensors through AI-Driven Design Support System

Francesco Campagna¹, Francesco Trevisan¹, and Ruben Specogna¹

¹EMC Lab, University of Udine, Udine, 33100 Italy

We propose a fast method to characterize inductive position sensors with zero physical prototypes. The technique is based on an in-house developed electromagnetic simulation tool which shows three orders of magnitude improvement with respect to the most widely used commercial software. This simulation software is used for producing synthetic data for training a machine learning surrogate model based on a neural network. In this way, the characterization of a sensor takes just milliseconds. This opens the possibility of devising a Design Support System (DesSS), a software that guide the user in sensor design for the best possible outcome, thereby saving development time.

Index Terms—encoders, inductive position sensors, electromagnetic simulation, machine learning

I. INTRODUCTION

Inductive position sensors (IPS) perform linear or angular position measurements [1]. Being contactless, low cost and immune to external magnetic field, temperature variations, dust and liquids they are preferred in those applications where the position measurements are performed in harsh environment.

An IPS consists of a transmitter (TX) coil (Fig. 1) which, being driven by an alternate current, establishes a variable magnetic field inside the sensor. In this region two receiver coils RX_{sin} and RX_{cos} (Fig. 1) measure induced voltages U_{RXsin} and U_{RXcos} . When a conductive target is positioned above the sensor, eddy currents are generated inside it. These eddy currents shield the magnetic flux in such a way that the induced voltage on the RX coils depend on the target position with a sine and cosine spatial variation. The position of the target can be determined thanks the following formula:

$$\theta_{meas} = \arctan \left(\frac{U_{RXsin}(\theta)}{U_{RXcos}(\theta)} \right) \quad (1)$$

The main drawback of these types of sensors is that the linearity error can often be unacceptably high. Therefore, accurately predicting this error through simulation tools is crucial for sensor characterization. However, finding a setup with low error is challenging since it involves finding the right combination of five or more design variables. For this reason, we aim to develop a DesSS to help users quickly find the best combination of these variables for their specific needs.

II. SIMULATION TOOL

For the virtual prototyping of the sensor, there is the need to solve many eddy current problems by varying the position of the target (Fig. 2). If Finite Elements tools are used, as implemented in most commercial software, the simulation speed is poor. In particular, when the target is moved, both the mesh and the simulation have to be recomputed from scratch.

A different strategy for IPS simulation uses the surface integral method [2]. The main advantage of such a method is that only the conductors are meshed, whereas the insulators are not. Thus, this method is very efficient especially for modeling

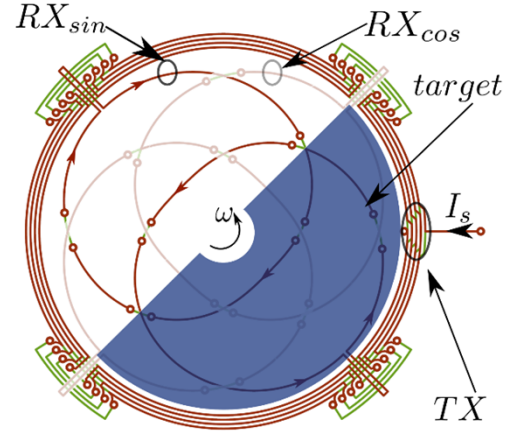


Fig. 1. An example of rotary inductive position sensor. The target is represented in blue.

eddy currents with moving conductors since the remeshing is not needed. The surface integral method is not widely used because the produced matrix is full and its entries are difficult to compute accurately because their computation involves the evaluation of a singular integral. The use of surface integral method for inductive position sensors has been introduced in [3]-[4].

In this paper we propose a new method called SUPERO, which constructs the matrix based on the novel functions recently introduced in [5] for a volume integral method. In place of using the standard Rao-Wilton-Glisson (RWG) or Raviart Thomas basis functions for the matrix construction, we designed new basis functions tailored for the surface integral method. This allows for highly efficient and precise assembly of the system matrix. Moreover, the full matrix can be sparsified obtaining unprecedented simulation speed. The results provided by SUPERO are very accurate and can be obtained 2500 faster than the most widely used commercial software.

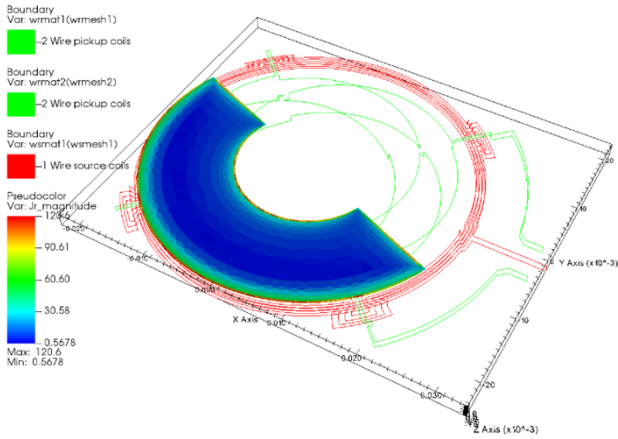


Fig. 2. Example of the simulated sensor with the surface integral method.

III. SURROGATE MODEL

With the new tool SUPERO, the simulation of 101 positions of an inductive position sensor can be performed in about 30 seconds, in place of roughly 24 hours needed with a FEM software. Still, 30 seconds to assess the linearity error of a sensor are not acceptable for many applications we have in mind. For this reason, we exploit the fast simulation tool SUPERO to produce many artificial data to be used for training a supervised machine learning method. The aim is to obtain a surrogate model which can estimate the error of a configuration in milliseconds. Three methods to build the surrogate model will be compared:

- 1) Support vector machine (SVM);
- 2) Gaussian processes regression (GPR);
- 3) Neural network (NN).

We used five design variables: maximal radius of the TX coil, minimum and maximum radius of the RX coils, minimum and maximum radius of the target. From these variables, we generated a dataset where each entry comprises a random feasible configuration describing a sensor, with the associated simulated error as the output. A total of 5000 designs were used for training, and 1800 for testing the surrogate model. The method that offers the best results in terms of training and prediction time, as well as forecasting accuracy for the linear error, is the neural network model. (Fig. 3).

IV. DESIGN SUPPORT SYSTEM

Using the surrogate model, the characterization of the error of an inductive position sensor can be performed in milliseconds. It is easy to imagine that by generating an error dataset using the model, fixing four design variables and varying the last one within a certain range, we can visualize the best value. It also becomes straightforward to leave only two variables free, as a heatmap with the error (Fig. 4) can help us choose the right parameters.

If, on the other hand, we want to use all the variables, we can no longer have an immediate response through visualization, so we need a DesSS software. In short, the DesSS software dynamically creates a dataset starting with all the variables. However, its primary purpose is to iteratively manipulate

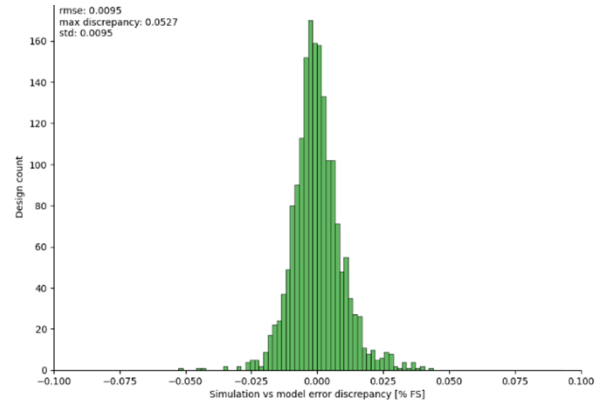


Fig. 3. Distribution of the discrepancy between the sensor linearity error provided by the simulation and the simulation error provided by the surrogate model based on a four-layer neural network.

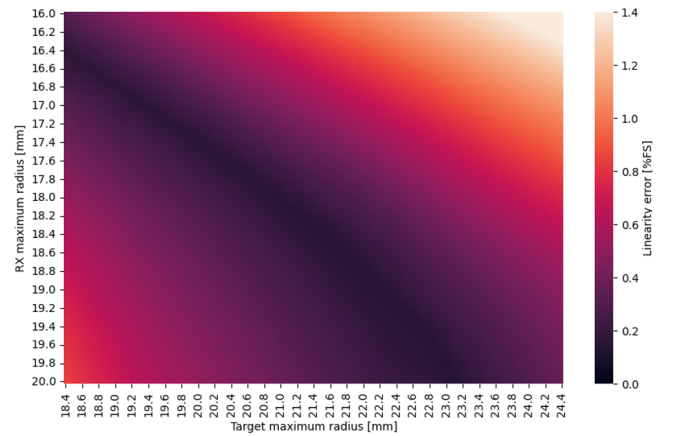


Fig. 4. Sensor linearity error as the maximum radius of the RX coils and target varies.

this dataset by fixing one desired parameter at a time and returning bounding boxes (allowable ranges) for the remaining. Importantly, these bounding boxes aren't just about finding the best parameters; they act as a helpful guide, assisting users in choosing parameters that meet the minimum error requirements. Moreover, if the user wishes, it is possible to directly optimize all or only some parameters to achieve the minimum error. The detailed functioning of the DesSS software and illustrative use cases will be discussed in the final paper.

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