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Systematic Optimization of Electromagnet Hardware for Electromagnetic Suspension: A Fusion of Simulation and Multi-Objective Optimization Techniques

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This paper introduces a novel multi-objective optimization (MOO) framework for the design of electromagnets in electromagnetic suspension systems. Traditionally focused on mechanical properties, electromagnet design often necessitates subsequent control system adjustments. Our approach aims to streamline this process by integrating mechanical design with controller performance from the outset. The paper highlights the inefficiencies of iterative design due to long production lead times and presents a solution through our proposed MOO framework. Key contributions include the development of the framework and its application in the simulation of an electromagnet, demonstrating a more efficient and balanced design approach.

Index Terms—**Multi-objective optimization (MOO), Electromagnetic Suspension (EMS), Design Optimization**

I. INTRODUCTION

THE design of electromagnetic suspension systems, notably for magnetically levitating (Maglev) vehicles, presents a multifaceted engineering challenge, traditionally approached from a predominantly mechanical perspective. This conventional methodology, while effective in addressing mechanical performance metrics, often overlooks the critical influence of electromagnet design on control behavior. In standard practice, control systems are subsequently tasked with compensating for design limitations inherent in electromagnets optimized solely based on mechanical properties.

This approach, however, is fraught with inefficiencies. The iterative optimization of magnet structures to better align with control requirements is time-consuming and resource-intensive. It involves extensive physical processes such as milling of steel and aluminum, winding of coils, and prolonged lead times for magnet production. This iterative cycle, while aiming for optimal integration with control systems, hinders rapid development and implementation.

In light of these challenges, our study explores an alternative approach. We propose a multi-objective design optimization (MOO) framework that concurrently considers both mechanical attributes and control system integration in the early design stages of electromagnets. This approach aims to streamline the design process, reducing the need for post-design compensatory adjustments in control systems. Related works have indicated the efficacy of MOO for electromagnetic systems. Whereas those approaches focus mainly on electrical machines and their electromechanical tradeoffs [1] [2] [3], our approach focuses on the impact of the controller performance based on the electromechanical properties.

Our main contributions are the following:

- In III, we present a comprehensive reference framework employing a multi-objective optimization algorithm for the preliminary design of electromagnets. An overview of this framework is depicted in Figure 1.
- In IV, we demonstrate the practical application of our framework through a simulated implementation, showcasing its efficacy in optimizing electromagnet design for improved integration with control systems.

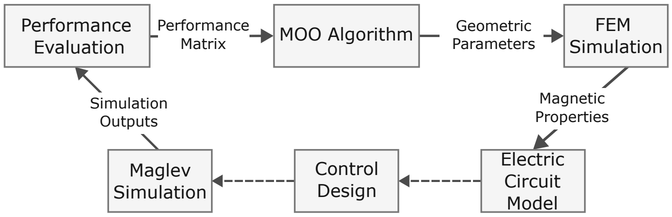

Fig. 1: Overview of the proposed optimization framework

II. BACKGROUND

A. Multi-objective Optimization

The goal of Multi-Objective Optimization is to identify a spectrum of optimal solutions balancing multiple, often conflicting, objectives. This leads to a set of Pareto-optimal solutions, each representing a different trade-off among the objectives. In addressing multi-objective optimization (MOO) problems, Bayesian optimization stands out for its efficiency, especially in situations where each objective function evaluation is resource-intensive. This approach requires fewer simulations compared to genetic algorithms like NSGA-II, which, while effective in navigating complex solution spaces, demand significantly more computational resources.

B. Electromagnet Design Influences on Control

In the design process of an electromagnet, it is crucial to consider various properties of the structure. In addition to the weight of the assembly, factors such as electrical resistance and both static and dynamic characteristics of the coil structure play a significant role in design and control. A key aspect is the magnetic force at different currents and air gaps, which directly influences the lifting capacity of the levitation system. To develop an effective control system, it is also essential to account for the inductance characteristics of current behavior. Conflicting considerations arise, as both parameters are dependent on the geometry of the structure, the winding characteristics, and saturation properties of the material. For example, a thicker core may offer a control advantage by delaying the onset of saturation in the core material, but the additional weight could unfavorably shift the operating point.

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The design of such electromagnets are a challenging task, for which various tools are available. For the modeling process, the Finite Element Method (FEM) is widely used to easily obtain detailed system characteristics. Based on this, it is possible to derive levitation simulations and control using system models such as an electric circuit model [4].

III. REFERENCE FRAMEWORK

This section presents our Reference Framework for the multi-objective design optimization of the electromagnet. The framework, as depicted in Figure 1 integrates an MOO-Algorithm with a FEM simulation and a Maglev simulation to yield Pareto-optimal design parameters for a set of performance metrics by influencing the mechanical attributes of the electromagnet.

To generate the necessary performance metrics, our framework incorporates an FEM simulation module that predicts the electromagnetic characteristics of the electromagnet. This data feeds into an electric circuit model [4]. This model is required to developing a responsive and efficient controller for the electromagnetic suspension (EMS) system, ensuring the electromagnet's optimal operation under dynamic conditions. With the controller in place, its real-world behavior is simulated within a Maglev system context. This step is crucial for understanding the controller's interaction with the electromagnet in a practical setting, offering insights into system dynamics and stability. Post-simulation, a performance evaluation module processes the results into a vector of performance metrics. These metrics encapsulate key aspects of system efficiency, reliability, and response characteristics. These performance metrics are then looped back into the MOO algorithm. This feedback mechanism is a continuous process, allowing for iterative enhancements in the electromagnet's design. Each iteration aims to converge towards an optimal set of design parameters, informed by real-world performance data. Our framework is designed to be a comprehensive tool for optimizing electromagnet designs in EMS systems, ensuring a systematic and data-driven approach to enhancing system performance and reliability.

IV. EVALUATION

In this section, we will apply out framework to the problem of Maglev development with the aim of generating insights in the dimensioning and control development process. Our optimization process begins with an electromagnetic simulation using ANSYS Maxwell. We start with a pre-defined electromagnet geometry, simulating its magnetic properties — force and inductance. These properties are influenced by the electromagnet's distance from the reaction rail and the current flowing through it, based on specified winding and iron parameters. The simulation results are utilized to train the magnetic suspension controller. This training ensures the controller effectively manages the electromagnet's operation in real-world scenarios. We then integrate the trained controller into a 1-D Maglev vehicle model simulation. This model, executed in MATLAB for 30 seconds, includes a passenger compartment and an undercarriage with the electromagnet. It's designed as a spring-damper system, compensating for gravitational forces and reacting to periodic disturbances (emulating track misalignments) to assess system stability.

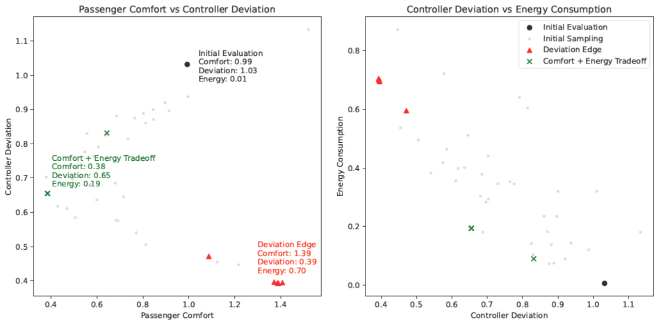

Fig. 2: Simulation results of electromagnet designs comparing passenger comfort, controller deviation, and energy consumption. Lower values in each metric denote higher performance.

The simulation yields key data: passenger module acceleration, electromagnet current, and the gap between the magnet and reaction rail. These metrics are crucial for evaluating passenger comfort, energy efficiency, and controller accuracy.

For system parameter optimization, we employ the Paref framework [5] with a Bayesian MOO algorithm. This approach allows us to set constraints, reducing the initial simulation evaluations required for effective optimization.

The results are illustrated in Figure 2, where the pre-defined initial evaluation is marked by a black dot and 50 random initial evaluations are represented as small grey dots. These initial samplings help the optimization algorithm understand the relationship between geometric parameters and performance metrics. The simulation incorporates two constraints: an edge constraint on controller deviation (indicated by a red triangle) and a trade-off between passenger comfort and energy consumption (shown as a green cross). The framework successfully identifies Pareto optimal solutions for both constraints.

V. CONCLUSION

Our study presents a novel Multi-Objective Optimization (MOO) framework, streamlining electromagnet design in Maglev systems. This innovative approach significantly reduces design time by integrating electromagnet and control system optimization from the start, diverging from conventional methods. While showing improvements in system performance in simulated environments, the framework demands further validation through real-world testing. This advancement represents a crucial step towards more efficient and rapidly developed Maglev transportation systems.

REFERENCES

[1] R. Lin, S. D. Sudhoff, and V. C. do Nascimento, "A multi-physics design method for v-shape interior permanent-magnet machines based on multi-objective optimization," *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 651–661, 2020.

[2] Y. Hua, H. Zhu, and Y. Xu, "Multi-objective optimization design of bearingless permanent magnet synchronous generator," *IEEE Transactions on Applied Superconductivity*, vol. 30, no. 4, pp. 1–5, 2020.

[3] S. Zheng, X. Zhu, L. Xu, Z. Xiang, L. Quan, and B. Yu, "Multi-objective optimization design of a multi-permanent-magnet motor considering magnet characteristic variation effects," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 4, pp. 3428–3438, 2021.

[4] K. Popp, W. Schiehlen, K. Popp, and W. Schiehlen, "Models for support and guidance systems," in *Ground Vehicle Dynamics*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 97–171. [Online]. Available: https://doi.org/10.1007/978-3-540-68553-1_3

[5] N. Palm, "paref: Problem tailored multi-objective optimization in Python," 2023. [Online]. Available: https://github.com/nicolaipalm/paref