Algorithm design for mixed-integer black-box optimization problems with uncertainty

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Chapter 7

Conclusion and Outlook

This thesis focuses on designing and tuning optimization algorithms that efficiently navigate through the complicated problem landscapes typical of real-world challenges in the design of vehicle dynamics control system parameters. Methods are presented for analyzing and improving the performance and applicability of optimization algorithms in solving computationally expensive mixed-integer black-box problems. Seven research questions posed in Section 1.2 are addressed in this thesis. The answers to these questions are summarized below.

In Chapter 3, the first research question is addressed by objectifying the desired behavior of the two control systems ABS and ARP. For example, the performance of the ABS parameters can be assessed through the braking distance, which enables the translation of the complex engineering problem into a quantifiable mathematical objective function. Defining the objective function of an engineering problem is a basic requirement for the application of optimization algorithms. Moreover, this objective function serves as the basis for subsequent algorithmic developments. To circumvent the computational costs of vehicle dynamics simulations, a comprehensive dataset is created using the workflow described in Section 3.3. Once created, this dataset serves as a complete replacement for the simulation with very low evaluation costs. Multiple optimization runs to obtain robust statistical results when benchmarking optimization algorithms on the real-world problem can be conducted time-efficiently.

Chapter 4 stands as a cornerstone of this thesis, addressing the second research question of how to tune optimization algorithm parameters for specific computationally expensive real-world optimization problems. The research explored the creation and use of computationally inexpensive surrogate problems to tune the parameters of an optimization algorithm. The similarity of optimization problems is quantified based on ELA features. This allows for precise calibration of algorithm parameters in a more computationally tractable but similar environment. The validation of the presented method through rigorous experimentation shows that the performance of CMA-ES can be significantly improved by using surrogate problems with similar properties to the original optimization landscape.

Furthermore, Chapter 4 contributes to answering the third research question, whether a universal parameter configuration can suffice for a class of related real-world problems or whether each instance requires a tailored approach. The research has shown that while a singular, well-tuned parameter configuration can indeed yield superior performance across different instances within a problem class, such as the design of vehicle dynamics control system parameters, there is also merit to the argument that individual problems may benefit from tailored parameter configurations. The meta-optimization framework developed allows for both strategies: tuning for general applicability or problem-specific optimization. The answer to the fourth research question is to define the identification of the optimal parameters of an optimization algorithm for solving a specific optimization problem as a meta-optimization task. The results of a comprehensive experiment show that compared to established algorithms such as SMAC and TPE, the use of CMA-ESwM as a meta-optimization algorithm is a cost-effective strategy for tuning the parameters of CMA-ES.

The parameters of the considered real-world problems are discrete, which raises the fifth research question addressed in Chapter 5: How does this discretization affect the optimization performance of the used optimization algorithm CMA-ES? The chapter presents a comparison and in-depth analysis of different CMA-ES variants and an extension of CMA-ES specifically designed to deal with discrete parameters. A spectrum of discretization levels and problem dimensionality is considered. The extension of CMA-ES, combined with strategic algorithmic adaptations, has demonstrated remarkable robustness in effectively handling the challenges introduced by discretization.

The sixth research question is: How can uncertainty in the objective function be quantified? Therefore, methods for the uncertainty quantification are presented in Section 2.7. Moreover, these methods can be combined with a DA policy described in Chapter 6, enabling the allocation of scenarios to individuals within a population dynamically. The presented methodology ensures efficient ranking with a high degree of confidence, which in turn reduces the number of evaluations required in uncertain landscapes.

The final research question asks about the advantage of combining this policy with CMA-ES. On the real-world problem, the computational resources saved throughout the optimization process are up to 26%. However, the proposed methodology is quite conservative. Thus, there is further potential for improvements by allocating fewer evaluations.

In a nutshell, by using the developed meta-optimization framework and specific extensions for CMA-ES, this thesis provides tailored CMA-ES configurations to solve mixed-integer black-box optimization problems with inherent uncertainty, such as the design of VDCS parameters. Furthermore, the developed meta-optimization framework is also applicable to other optimization algorithms and optimization problems beyond the scope of VDCSs.

From this thesis, several promising avenues for future research emerge. One potential direction is to extend the tuning methodology presented in Chapter 4 to other real-world problem classes. Moreover, this allows for the analysis of the differences and similarities of these problem classes, such as vehicle dynamics, vehicle crash, or even non-vehicle domains, such as economics or finance. Furthermore, a database that stores and uses information from previous tuning and optimization runs can provide a path to enhance the efficiency of the developed method. Finally, an open research question is the extension from single-objective to multi-objective optimization, especially in the context of algorithm tuning.

As highlighted in Chapter 5, future research may address strategies for managing high-dimensional settings with numerous discrete levels. Improving the efficiency of uncertainty quantification in optimization algorithms, such as CMA-ES, as discussed in Chapter 6, also provides fertile ground for research.

The methods and findings presented in this thesis narrow the gap between the application of sophisticated optimization algorithms and computationally expensive black-box problems. These methods provide a basis for future developments and improvements in vehicle design and control as the automotive industry and scientific research continue to evolve.