Visualization of heuristic-based multi-objective design space exploration of embedded systems
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In this thesis, we addressed the visualization of multi-objective design space exploration of multi-processor system-on-chip architectures. Actually, we built a bridge between two previously separate research fields. We introduced the structural usage of data visualization into the field of embedded systems design. For performing a comprehensive study of the DSE process, we defined three separate stages and for each stage, we developed several methods and visualization techniques to provide users a rapid and more accurate analysis. A detailed description of each stage as well as the proposed visualization approaches were presented in the previous chapters.

In this chapter, we first summarize the thesis and then we describe the remaining open issues and future directions.

6.1 Outlook

In this thesis, we presented our novel interactive visualization tool, called VMODEX. All the proposed methods and visualization techniques for supporting the design space exploration of embedded systems are incorporated in VMODEX. The work presented in this thesis can be summarized as follows.

In Chapter 2, we gave an overview of the background information necessary for the rest of the thesis. We first described the basic knowledge about multi-objective optimization problems. Then, we explained the multi-objective optimization problem in the context of design space exploration of embedded systems. Afterwards, we discussed the benefits of using visualization techniques for exploring and analyzing the large amounts of data. Finally, we concluded this chapter and illustrated the need for employing efficient visualization methods for interpreting and gaining insight into the DSE results.

In Chapter 3, we introduced our tree model of the design space. In our DSE tree, both the design parameters and criteria are shown in a single view. Several interactive capabilities are provided to be able to handle large design spaces and allow designers to look at the data from different perspectives and at multiple levels of abstraction.
Furthermore, in our DSE tree model, we defined the concepts of subspaces and local Pareto points, which are new concepts in the multi-objective DSE process and have not been considered before. In VMODEX, besides the techniques provided for visualizing the DSE results, additional capabilities are developed to understand the dynamic search behavior of heuristic searching algorithms that are typically used in the DSE process. This chapter supports the second stage of multi-objective DSE, which is exploring the design space and analyzing the results.

Chapter 4 is dedicated to the first stage of multi-objective DSE, which is evaluating the performance of different multi-objective optimizers and finding the best one for a specific problem. In this chapter, we introduced various performance metrics (both existing and new metrics) and their visualization methods we have provided in VMODEX. In multi-objective optimization problems, several distinct goals need to be achieved and therefore there cannot be a single quality measure that indicates the performance of an optimization algorithm in an absolute sense. Thus, various metrics need to be used to perform a comprehensive analysis of the performance of an optimization approach. Most of the current performance measures concentrate on evaluating the quality of found Pareto optimal solutions in the objective space and measuring the behavior of the optimization algorithm in the decision space has mostly been disregarded. In this thesis, we turned the focus of attention from exclusively evaluating optimization success in the objective space to also considering the decision space. In this chapter, we defined new goals and subsequently new metrics to evaluate the behavior of optimization methods in the decision space.

In Chapter 5 we addressed the last stage of multi-objective DSE, which is the decision making process. As the last step of the multi-objective DSE process, the decision maker should select the most preferred design point from the set of Pareto optimal points for the final implementation. In this chapter, we explained the Multi-Objective Decision Making (MODM) methods that are provided in VMODEX and can help decision makers to understand the trade-offs between different criteria and select the final solution for the implementation. Furthermore, we proposed new visualization approaches, which provide the visual interpretation and detailed analysis of the results of the MODM methods. In this chapter, we described the four basic problem formulations in MODM, which are: choice, classification/sorting, clustering and ranking problems. For each problem formulation, some decision making methodologies and their proposed visualizations are explained. In this chapter, we defined a new method addressing the choice problem, which is based on the fuzzy dominance relations between the Pareto optimal points. Furthermore, we proposed a new preference similarity measure for clustering the solutions. In our proposed similarity measure, unlike the conventional measures, the decision maker’s preferences are integrated in the multi-objective cluster analysis. In addition, we introduced a scheme for constructing the cluster centers, considering the properties of all solutions inside the same cluster. Some clustering approaches utilize the concept of cluster center for assigning the objects to different clusters.
6.2 Open Issues and Future Directions

The research presented in this thesis is still in progress. There are several interesting further research directions in terms of extending the proposed visualization techniques to support additional aspects of the design space exploration process. For instance, in this thesis, we consider the problem of the mapping of only one parallel application onto a heterogeneous MPSoC architecture. However, embedded systems often need to support multiple applications simultaneously. There is an opportunity to extend our proposed tree model of the design space to be able to support the design space exploration of embedded systems with multiple target applications. The work in [109, 110] introduced a scenario-based design methodology for embedded systems with multiple applications. They distinguished two types of dynamic behavior: intra-application and inter-application. The intra-application dynamism describes the changing behavior of an individual application, whereas inter-application dynamism describes which subset of applications can run concurrently. New visualization approaches can be developed to enable designers to gain a better understanding of the dynamic behavior both within and between applications.

Another possible research direction is providing the interaction between the visualization and simulator. Instead of having a one-way flow of information from simulation to visualization, it is useful to provide mechanisms for interactive feedback from visualization to the simulator. This kind of interaction allows designers to directly steer the simulation process. For instance, by using the visualization, the designer may notice that in some parts of the design space there is no evaluated design point. The searching algorithm could not access to those parts of the design space. However, if the designer is interested to know about the properties of solutions in some unexplored parts of the design space, he should be able to interact with the simulator to generate some random design points in those parts and then continue the searching process for a specified number of iterations. Another example of possible interaction with the simulator is requesting to evaluate a specific design point that has not been evaluated during the exploring process. For instance, in investigating the effect of different mappings on the design criteria, some desired design points might not be visited by the searching algorithm. So, the designer can interact with the simulator and request it to evaluate those particular design points.

Another open issue that is not addressed in this work is proposing visualization methods that take into account the average behavior of several runs of an optimization algorithm. The visualization techniques that we explained in Chapter 4 address the analysis of results from a one-shot algorithm execution. Nevertheless, the same as comparing different algorithms, several runs of the same algorithm can also be evaluated and compared by our proposed visualization techniques. However, in our future work, we are going to extend our visualization approaches in order to show the average performance of an algorithm during numerous runs (with respect to a specific aspect) in a single view.

It should be mentioned that our work in this thesis is just one possible approach for
visualizing the multi-objective DSE process. It is indeed an open issue in this domain to examine other alternatives for visualization and compare the efficiency of different approaches. Furthermore, as a future work, we intend to ask end users to use our visualization tool for analyzing their DSE results. Their feedback will be used to evaluate as well as improve the efficiency and effectiveness of our tool.