Chapter 9
Reflections on the Octopus Project

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Abstract How to develop adaptive high-tech embedded systems? This question has motivated this book. Adaptivity provides a wider operational envelope of systems and enables new market opportunities. Effective development of such systems requires a systematic approach that enables to include the adaptive capabilities at various system levels. This book presents the most important results of the Octopus project. Being an industry-as-laboratory project, Octopus brought together academic partners and engineers from Océ-Technologies. Industrial challenges in professional printing motivated the research and results were validated in industrial practice. This approach turned out to be successful, with results ranging from improved control schemes for adaptive inkjet printing to design-space exploration tooling for embedded electronics and architecting patterns for adaptive embedded systems. Octopus confirmed some important points of attention for industry-as-laboratory projects. First, the paradigm needs academic researchers with a strong motivation to improve the industrial state-of-the-art. Second, it is not always easy to combine progress of industrial practice with scientific progress. A crisp definition of industrially relevant and academically challenging driver cases is crucial.

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9.1 Introduction

The Octopus project was a follow-up of the successful BodeRC project [1], which brought a number of results for Océ and promising new research directions. The "HappyFlow" model concerning the paper flow in printers has enabled to reduce the printer development time significantly, because the model allows virtual exploration of paper path designs.

The impact of this result alone saved many man-years of effort and reduced time-to-market of newly developed printers. The process of creating models however was not perceived as transparent. So, further research into transparent methods to construct models on different system levels constituted a promising new research direction. The use of models offers high potential savings in development effort and costs, and a further reduction in product creation lead-time.

The Octopus project was initiated to further explore the insights of BodeRC. The project's research was focused on methods to design key properties of future printing systems that are expected to operate in a diverse and highly dynamic business environments, with continuously changing requirements for context, function, application, and technology. In order to ensure the competitive positioning of such systems in a global market, it has become of paramount importance to include the correct level of system adaptability in the design.

The objective of the Octopus project has been to find concepts, methods, and tooling for the design of printing systems with an adequate adaptability at system, subsystem, and component level. Central to these concepts is the transparent coordination of system control over different technology domains making use of multi-disciplinary models. This coordination should be supported by systems architectures that intrinsically facilitate adaptability. The resulting methods serve to incorporate run-time adaptability features in such a way that high-quality prints can be produced for a wide variety of media types (even new ones) under varying environmental conditions. Although the goals were made specific for the professional printing domain, they are relevant for the high-tech embedded systems industry in general.

Looking to the research content the subjects can be grouped in two categories of subjects, the first being control of embedded systems and the second being architecting and design of adaptive embedded systems. This division of subjects has been followed in the preceding chapters and is followed in this reflection chapter as well.

From an organisational point of view, the Octopus project was defined under the Dutch BSIK regulations as a research project in an industry-as-laboratory setting [2] with consortium partners Océ-Technologies B.V., the Embedded Systems Institute, Delft University of Technology, Eindhoven University of Technology, Radboud University Nijmegen, and the University of Twente.

This chapter reflects with a bird's-eye view on the outcome of the Octopus project. Section 9.2 provides an overview of the most important results. A reflection on the impact and the key lessons learned is to be found in Sects. 9.3 and 9.4, respectively. Section 9.5 presents some conclusions.

9.2 Overview of Technical Results

We provide an overview of the results of the project, following the partitioning made in Chap. 1 into “control of adaptive embedded systems” and “architecting and design of adaptive embedded systems”. Along this division, we discuss the industrial impact of the results.

9.2.1 Control of Adaptive Embedded Systems

Control of adaptive embedded systems was the topic of Chaps. 3–5. This section describes the main results of these chapters.

Adaptive control of inkjet printheads. In Chap. 3, different feedforward control schemes were presented. New model-based and experiment-based control schemes for jetting pulses have been developed for the single-channel and multiple-channel printhead use cases with considerable print quality improvements, beyond the current state-of-the-art. The main ingredient for these results is the obtained independence of the ink jetting process from its frequency of operation and the requested payload.

Adaptive control at system level. Chapter 4 presented and compared approaches to system-level adaptive control; this involved two approaches to model reference adaptive control (MRAC) and two for model predictive control (MPC). Each of these approaches has its own merits. Chapter 4 showed that the MRAC approaches offer a robust performance at low costs, whereas MPC allows the best performance at the cost of a higher computational load. Both approaches provide an improvement over the current state-of-the-art, as overall better trade-offs in the quality/time/cost triangle can be obtained.

Probabilistic graphical models for adaptive control. The fuse temperature is a key factor for the print quality and is determined by many mutually dependent parameters. A new control approach for the fuse temperature using Bayesian network models has been developed. It was presented in Chap. 5. This novel approach resulted in a patent application [3]. Another new Bayesian network model application involves a classifier that can discriminate between different print media through deduction from the behaviour of the print process.

9.2.2 Architecting and Design of Adaptive Embedded Systems

Chapters 6–8 discussed architecting and design of adaptive embedded systems. The main results of these chapters are listed in this section.

Systematic support for systems architecting. Chapter 6 presented a new approach and tooling to support the first phases of systems architecting. System specifications with physical phenomena lead to parameter network models that involve the key parameters of a system and their relations. This is the starting point for different embodiments of the system in terms of subsystems and architecture. Selected options can be analysed both qualitatively and quantitatively. The approach has been demonstrated with a first example, implemented with extensions of the KIEF prototype tooling [4].

Methodology and tool set for design-space exploration. Chapter 7 presented a tool set for design-space exploration. This Octopus tool set has been verified on several printer data path use cases. Different methods can be combined to generate visualisations of system performance metrics based on (graphical) system specifications. Because of the complex processing steps, industrially sound tooling is required. An open architecture has been designed for a tool set that allows flexible deployment, future changes, and incorporation of add-ons. The impact of combined application of the methodology and the tool set is high: improved accuracy in specifications, better understanding of system behaviour through visualisations, much faster exploration of design options, and improved documentation. All together this leads to faster system development.

Architecting and design of adaptive software. Chapter 8 considered model-based development of adaptive software applied to two industrial cases. One case involves a new method to construct the software architecture of a physical system with clear separation of software components dealing with system resources, system behaviour, and the control of system behaviour. An architectural style, called MO2 (Multi-Objective Optimisation), has been developed to structure the software of a system in which objective trade-offs must be made at run-time. A tool framework was developed and it was demonstrated how it supports software architecting. The other case concerns model-based design of scheduling systems. The chapter presented a scheduling specification language called scheDL and a supporting tool framework to accomplish executable scheduling models for simulation. The simulation results provide feedback on the performance of the proposed solutions to the engineer for possible improvements of the system scheduling policy.

9.3 Impact

This section summarises the impact of the Octopus project.

Strategic benefit. The project has provided Océ with an important early inflow of scientific knowledge that is required to tackle high-risk long-term industrial challenges with potential high impact. The project has brought new research problems to ESI and the academic partners. The leverage for all stakeholders justifies the total investments from an economic, societal, and financial perspective.

Improved design effectiveness. The emphasis on model-based design methods has enriched the existing basis of effective model-based design at Océ. New concepts and methods have been introduced to develop models for industrial cases such as data path design-space exploration, multi-channel inkjet control, and system-level printer control. Tooling has been built to support the introduction of the scientific concepts and methods for industrial application. The combination of methods and tools offers support to achieve high design quality, design speed, and improved team communication while design effort and thus lead-time and costs decrease.

Industrial embedding for education. The project has provided an excellent embedding for education of highly skilled professionals. The academic researchers and industrial researchers have cooperated on design-space exploration methods applied to printer data paths, control approaches applied to inkjet printheads, and methods for systems and software architecting applied to adaptive printer system control. A substantial body of knowledge has been developed by the academic project partners. There are 16 senior academic researchers, 8 postdoctorate researchers, and 7 PhD students of 7 distinct academic groups who have extended their scientific knowledge. One postdoctorate researcher has been awarded an academic "Veni" grant. A group of 16 PDeng students was guided on basis of an Octopus assignment (in total 2 man years of education effort), and 5 PDeng students conducted their final projects (each 9 months) in Octopus. The project has hosted 13 master's students for their master's theses with subjects instigated by the Octopus project research.

Scientific publications. Throughout the project the research team published more than 100 scientific publications including journal papers, conference contributions, technical reports, PhD theses, and master's theses. An overview of these publications can be found in Appendix B.

9.4 Reflection

The cooperation between Océ, ESI, and academic partners in industry-as-laboratory research projects like Octopus is evaluated in this section. Especially the learning points are discussed.

Focus on one integrated business case. It is needed to have a realistic and challenging use case as a carrier for intensive information exchange between the involved academic researchers and industrial developers. A proper problem should fit genuine business goals of the carrying industrial partner. Starting the project with finding one business case incorporating clear research questions with a proper scope that enforces cooperation across all members of the research team is therefore recommended. Spending sufficient time to find shared goals and to gain deeper understanding of each other's interests is needed. This stimulates cooperation between project partners across research lines to solve the "big" shared problem in an optimal way.

Requirements on personal skills. The recruitment of research staff for Octopus was an intensive process with much effort of the academic supervisors to find suitable candidates. We have learned that successful industry-as-laboratory projects need researchers who want to and are able to cross the borders of their own academic discipline to other academic and industrial disciplines: PhD students and postdoctorate researchers have to satisfy both academic and industrial goals with a suitable mix of qualities. This is the most prominent lesson learned for all involved project partners. It will lead us to the introduction of selection methods that go beyond the standard job interview.

Timely acquisition of domain knowledge. At the start of the project the research team had very little detailed knowledge of the domain in which they would be working. Investing time and effort of all partners to give the team a firm basis in the core technology and business goals of the carrying industrial partner is very important to put the research objectives into perspective. An internship of a few months at the start of the project is expected to substantially accelerate the acquisition of domain knowledge by the academic researchers. This hold primarily for the "embedded" researchers themselves, but to some degree also for their supervisors.

Management of disruptive technology changes. The Octopus project started with research topics that focused on "direct image printing" technology as the key business driver. During the project "inkjet technology" became the primary business driver. This kind of major technology change must be considered a "fact-of-life". The key learning point here is that we have to develop a better awareness that such disruptive changes may happen during the life-time of a project, with big impact for the research focus and activities. Such changes require activities that normally belong to the start-up period of a project, e.g. acquiring new domain knowledge. The adoption of new technologies in industry needs management focus on strong involvement of industrial (Océ) staff and strong interaction with academic researchers for real implementation.

Positioning of research subjects. Academic groups provide excellent and highly valuable new results to a project, as was the case for Octopus. Combining these new technologies into system-wide solutions, and integrating them into an architectural framework requires competences which not all academic researchers have. In order to make such complicated multi-disciplinary projects into a success, "systems architecting" must be incorporated as one of the key project components. Architecting considerations must be introduced ahead of – or in the earliest stages of – the project, as these must define the context, objectives, and boundaries of the individual academic partners. This allows integration of the contributions of each individual partner into a strong, integrated use case with high business relevance.

9.5 Concluding Remarks

This chapter concludes the book "Model-Based Design of Adaptive Embedded Systems". The book summarises the achievements of the Octopus project. The project team took up the challenge to find answers to various aspects of the research question "How to develop adaptive embedded systems?".

The value of the "industry-as-laboratory" project approach has been confirmed by the project outcomes for all partners involved in this research journey. The project leverage justifies the total investments from economic, societal, and financial perspective.

The concluding remark in the project's final review meeting by the vice president of Océ responsible for the project nicely summarises the project and its impact: "We can be pleased with how far we got, but we want more! So we will extend activities on the topics touched upon in Octopus". This is being done in Octopus' successor project, Octo+,[1] the third industry-as-laboratory project of Océ-Technologies and the Embedded Systems Institute.

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[1]More information on the Octo+ project can be found on the project's website: http://www.esi.nl/octoplus/.