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Control-Based Operating System Design

Alberto Leva, Martina Maggio,
Alessandro Vittorio Papadopoulos
and Federico Terraneo

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To Clara and Aurora, with love.
(A.L.)

To my parents, for their unconditioned love.
(M.M.)

To my grandfather, my parents, my sister, Ettore and Anna.
(A.V.P.)

To my father and my mother, for their support.
(F.T.)

It was stated at the outset,
that this system would not be here, and at once, perfected.
You cannot but plainly see that I have kept my word.
But I now leave my cetological System standing thus unfinished,
even as the great Cathedral of Cologne was left,
with the cranes still standing upon the top of the uncompleted tower.
For small erections may be finished by their first architects;
grand ones, true ones, ever leave the copestone to posterity.
God keep me from ever completing anything.
This whole book is but a draught—nay, but the draught of a draught.
Oh, Time, Strength, Cash, and Patience!
H. Melville, Moby Dick, 32

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Preface

Most often, a research topic becomes the subject of books when it is approaching maturity, and a significant *corpus* of results and applications is available.

As suggested in the introductory quote, the story of this book is quite different. When we started approaching the design (not just the control) of operating system components in a system-theoretical manner, we were in fact quite surprised how sparingly the computer science and the control community have been interacting so far, at least in the sense described herein. Crudely, after a few years of research on the matter, we decided to write this book because we are convinced that the proposed approach is an important step forward with respect to present design practices, but to explain why and how clearly enough, too much space is required to comply with any other form of publication.

As such, this book is indeed 'but the draught of a draught'. Its main purpose is to sketch out a research path that can be reasonably expected to last for several years, providing some results to justify the required effort.

To this end, we decided to include some chapters on systems and control theory. These are in no sense to be thought of as a course on the matter. On the contrary, we tried to present only what is needed to follow and understand our proposals, addressing essentially a computer scientist who has little or no knowledge on the systems and control theory. The only constraint we adhered to is to provide a consistent treatise without conceptual jumps, but no doubt a number of important subjects are here omitted. For the convenience of the reader coming from the control community, on the other hand, we briefly present each addressed object and problem, thus reporting ideas and facts that for the computer scientist are totally obvious. We hope that this helps both types of reader feel comfortable with the text.

In the book we also provide some results, basically addressing a collection of problems that traditionally are not viewed from the control standpoint, to show the insight and simplicity enhancements that such a viewpoint conversely yields.

Overall, the book is organised as follows:

- Chapter 1 provides a general introduction to the addressed matter and motivates the adopted approach, also by means of a very synthetic historical analysis.
- Chapter 2 introduces the few required basic elements of systems theory, as anticipated. This chapter and the following Chapter 4 end with a 'problems' section, to allow the interested reader to verify his/her acquisition of the illustrated concepts.

- Chapter 3 applies the modelling-related ideas of Chapter 2 to the particular domain addressed herein, evidencing its peculiarities. Some introductory examples are reported and commented on.
- Chapter 4 deals with the required basic elements of *control* theory, adopting an attitude, and consequently an organisation, analogous to those of Chapter 2.
- Chapter 5 deals with task scheduling. A general dynamic model is proposed, and based on that, a methodology is presented to design a scheduler along the control-based paradigm. Said methodology is then applied, leading to two scheduling algorithms, that are comparatively tested with respect to classical (non-control-based) ones.
- Chapter 6 addresses the problem of memory management, and proposes for it too a control-based solution. Simulation results are presented and commented on, to evidence the obtained advantages.
- Chapter 7 presents, limiting again the scope to the bare essential, some control techniques – more advanced than those of Chapter 4 – that are used in the following one. In particular, the chapter deals with Model Predictive Control and model identification, and ends with a 'problems' section for the same reason as Chapters 2 and 4.
- Chapter 8 treats more in general the resource allocation problem. Thanks to the adoption of more a high-level viewpoint with respect to the previous chapters, here a design methodology is sketched out and supported, that can be used as a *modus operandi* when addressing numerous problems that appear quite different from the application point of view, but in the context of the systems theory have a definitely uniform mathematical structure.
- Chapter 9 applies the ideas presented so far to power-aware resource management. Apart from discussing another interesting application case, the main point here is to evidence how a control-based design attitude is naturally keen to host problems with very different requirements.
- Chapter 10 presents the Miosix kernel, i.e., the nucleus of an operating system that is being developed along the proposed approach. Motivations for developing an *ad hoc* kernel are provided, the realised functionalities are described, and future developments are outlined.
- Chapter 11, after all the different issues touched in the previous ones, suggests a way of casting them into a unitary view conceptually connected to that of 'cyber-physical' systems, thereby discussing – as a work in progress – some further ways in which a control-theoretical point of view can be helpful for design, analysis and assessment.

Chapters not related to introducing systems and control theory material do not have a 'problems' section for quite apparent reasons. The interested reader is, however, encouraged to try out the presented solutions, and also to use the approach to design and test his/her own ones, based, e.g., on the Miosix kernel, and the code examples reported in Appendix A. In particular, the reader – especially the computer scientist – is encouraged to use dynamic models for design, and to test the devised solutions by means of dynamic simulation.

Among the functionalities of the typical operating system, scheduling receives in this book quite significantly a dominant attention. This choice was dictated basically by two reasons. The first is that scheduling is undoubtedly a core functionality, and in some sense maybe the most important one. The second is that we wanted to present a complete solution, illustrating the proposed approach from the modelling phase till the realisation of the necessary code, so as to show the importance of giving the design process a system-theoretical flavour wherever possible and applicable. Quite intuitively, doing the same for all the functionalities mentioned and addressed in the book would have lead to a lengthy treatise with numerous repetitions. The abstraction and re-interpretation capabilities of the reader, in our opinion, can certainly suffice to allow him/her to re-apply the proposed ideas in different contexts, and for this reason only some guidelines for such re-applications are provided.

On the same front, several components that are considered part of an operating system – e.g., the file system – are not treated at all. In fact, as the book title, we might as well have chosen 'Control-based *kernel and operating system services* design'. On one hand doing so would probably have better reflected the detailed book content, but on the other we have the impression that it would have somehow limited the view on the potentialities of the proposed approach. We hope that after going through the book, the reader can share with us the belief that once a kernel and its services are designed and assessed as suggested, the rest of the operating system can rely on them and take profit of said design in quite a straightforward manner. The concluding remarks of Chapter 11 will further deal with this particular topic.

The book attempts to maintain an intermediate attitude between presenting solutions, which should help the computer scientist appreciate the usefulness of the approach, and evidencing the need for a more methodologically grounded treatise of some issues that tend to be considered, especially in the control community, as implementation-related matter of facts.

The authors are not sure at all that the best compromise between those two attitudes was here found, but hope that the effort will be appreciated, and even more important, that the *necessity* of such an effort will be acknowledged. Of course, the establishment of both a comprehensive 'systems and control theory for computer science' and of the consequent engineering principles is a formidable task, of which we do not claim here to present but the very initial steps.

We correspondingly understand that the perspective shift here proposed is significant indeed, and although we did our best to keep in mind implementation-related facts, we expect that besides some certainties, the matter exposed herein will most likely give rise to discussions. We hope that this happens, because the solutions proposed here can surely be improved, and doing this together would culturally enrich both the computer and the control community.

In fact, we believe that the foreseen convergence of the two communities just mentioned not only is highly beneficial for both, but given the steady complexity increase experience in virtually any domain related to computing systems at large, it may well become a necessity not so far in the future. As such, we strongly hope

that this work, despite the undoubted imperfections of a research path that started out quite recently, can not only allow to appreciate some nice results, but above all foster a more strict inter-domain cooperation.

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Federico Terraneo

December 2012

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This book contains our personal views on Control-Theoretical Design of Operating Systems, and our opinions were influenced by various sources. To start, we would like to thank our colleagues, who have contributed to shape our mind and to the design and implementation of some of the work presented in the following pages. During an early stage of development, Carlo Alberto Furia and Paola Spoletini provided very useful insight and comments on the scheduling problem. The resource allocation problem was extensively discussed with Anant Agarwal, Marco Domenico Santambrogio and Jacopo Panerati, whom we thank for their invaluable help; also the help of Sara Negro was important in this respect. A lot of the inspiration for this book came from Henry Hoffmann's work on the Application Heartbeat and SEEC project. His contribution — both theoretical and practical — was inestimable and we would never have written this book without his support. Riccardo Scattolini helped with his long experience, particularly by reviewing the chapters on basis systems and control theory, and many other colleagues involved in Automatic Control (the list would really be long) contributed with discussions and suggestions. Finally, we would like to thank Antonio Filieri and Carlo Ghezzi. Even if the research we carried on together has no place in this book, our interaction cleared our mind and allowed us to face problems with a different mindset.

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