Lecture Notes in Computer Science 1062
Edited by G. Goos, J. Hartmanis and J. van Leeuwen

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Towards Evolvable Hardware

The Evolutionary Engineering Approach

Springer

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Cataloging-in-Publication data applied for

Die Deutsche Bibliothek - CIP-Einheitsaufnahme

Towards evolvable hardware : the evolutionary engineering approach / Eduardo Sanchez ; Marco Tomassini (ed.). - Berlin ; Heidelberg ; New York ; Barcelona ; Hong Kong ; London ; Milan ; Paris ; Santa Clara ; Singapore ; Tokyo : Springer, 1996
(Lecture notes in computer science ; 1062)
ISBN 3-540-61093-6
NE: Sanchez, Eduardo [Hrsg.]; GT

CR Subject Classification (1991): B.6, B.7, I.6, I.2.9, I.5, J.2, J.3

ISBN 3-540-61093-6 Springer-Verlag Berlin Heidelberg New York

Typesetting: Camera-ready by author
SPIN 10512708 06/3142 – 5 4 3 2 1 0 Printed on acid-free paper

Preface

During the past few years, we have been witness to a merging of innovative ideas with powerful technologies, breathing life into the old dream of constructing biological-like machines. This theme was first raised almost fifty years ago, during the post war era, by the founding fathers of cybernetics, most notably John Von Neumann. Central to his final work were the concepts of self-reproduction and self-repair; unfortunately, the technology available at the time was far removed from that necessary to implement his ideas. The years that followed have seen the rise, fall, and eventual resurgence of artificial neural networks, along with the recent advent of artificial life, spearheaded by Christopher Langton. Another novel idea which surfaced during this period is that of applying evolution to artificial systems; pioneered most notably by John Holland, this concept was slowly making headway, finding its place in the more traditional engineering disciplines as well as within the artificial intelligence community. In retrospect, it seems we had to patiently wait for almost four decades in order to translate these abstract ideas into working machines.

The remarkable increase in computational power and, more recently, the appearance of a new generation of programmable logic devices, have made it possible to put into actual use models of genetic encoding and artificial evolution; this has lead to the simulation and ultimately the hardware implementation of a new brand of machines. We have crossed a technological barrier, beyond which we no longer need content ourselves with traditional approaches to engineering design; rather, we can now *evolve* machines to attain the desired behavior. This novel approach has been quite appropriately named "evolutionary engineering", and, although we are just taking our first steps, it promises to revolutionize the way we design our future machines; we are witnessing the nascence of a new era, in which the terms 'adaptation' and 'design' will no longer represent opposing concepts.

Natural evolution implies populations of individuals, each possessing a description of their physical features, known as the *genotype*. A new generation of individuals is created through the process of reproduction, in which genotypes are transmitted to the descendants, with modifications due to crossover and mutation. These genetic operations take place in an autonomous manner within each entity, that is, within the genotype; the resulting physical manifestation of an individual, known as the *phenotype*, is then subjected to the surrounding *environment*, which, through a culling process, preserves only the better adapted individuals. The evolutionary process has no central controller nor any ultimate goal toward which it strives; an individual's fitness is *implicitly* determined by its ability to survive and reproduce in the surrounding environment.

Direct application of these principles to hardware evolution is by no means a simple effort. Currently, we observe two different paths which are taken, dubbed "intrinsic" and "extrinsic" by de Garis and "on-line" and "off-line" by Kitano. In the extrinsic or off-line case, evolutionary design is carried out as a software simulation, with the resulting satisfactory solution (design) then used to configure the programmable hardware. In intrinsic or on-line hardware evolution, each individual is an autonomous physical entity, ideally capable of modifying itself; this occurs as a result of directly sensing feedback signals communicated by a suitable physical environment and possibly by other members of a population of similar entities. To date, on-line evolution presents practical difficulties and the genetic operations (selection, mutation, recombination) are usually performed off-line, in software.

We felt that the time was ripe for assessing the state of the art in this novel interdisciplinary field, carefully evaluating current impediments and future developments. An international workshop, entitled "Towards Evolvable Hardware", was thus held on October 2-3, 1995 at the Logic Systems Laboratory in the Computer Science Department, Swiss Federal Institute of Technology. The workshop was attended by all major groups working in the field, at least to our knowledge. This volume contains the works presented therein, and is intended to serve both as a description of state-of-the-art research in the field as well as an intelligible introduction of the basic concepts.

The first two chapters, by E. Sanchez and M. Tomassini, are intended as an introduction to programmable logic devices and evolutionary computation; of particular interest are FPGAs (Field-Programmable Gate Arrays), genetic algorithms and genetic programming, along with notions of parallel implementation. Though a number of introductory volumes are available on these subjects, we feel that these chapters serve to make this book more self-contained. The chapters by F. Gruau and H. de Garis deal with new software techniques for evolving complex neural networks. These techniques benefit from high-performance parallel simulation platforms, with the potential of being applied to actual evolvable hardware. The paper by H. Hemmi *et al.* describes a system for the evolution of high-level descriptions of a piece of hardware. At the end of the search the best result is dowloaded to a real programmable circuit. H. Kitano, Higuchi *et al.*, and Harvey and Thompson present methodologies that display different degrees of intrinsic evolution, demonstrating original applications and offering several important suggestions for further development of the field. We believe that showing working applications of intrinsically evolved hardware, however simple they are to date, is extremely important for the field's future. P. Marchal *et al.* and D. Mange *et al.* are working in a somewhat different direction. Their project, "embryonics", is concerned with the construction of multicellular digital organisms in a cellular array, with each individual organism containing its entire "genome", or plan. Cell differentiation, and thus function specialization, is achieved by having each cell activate only those genes within the genome that correspond to its function in the overall design. Their approach displays self-reproduction and differentiation, also offering self-repair capabilities; while potentially capable of evolution, the genetic operations are not yet implemented. Kitano suggests in his paper some interesting ideas for merging the embryological and evolutionary aspects. Mobile autonomous robots are the subject of Mondada and Floreano's chapter. In their approach, physical robots learn to perform various tasks through interactions with a physical environment which they inhabit. At the heart of the robot's sensory-motor control is a neural network which is genetically evolved, with the robot's performance serving as a fitness measure. Although the genetic algorithm is implemented in software (i.e., off-line), the robots themselves posses a physical embodiment; in addition, experiments have been carried out involving several interacting robots. We share Mondada and Floreano's belief that human-like, or perhaps more humbly insect-like, intelligence can only possibly evolve by pursuing such an approach; physically embodied entities learn to perform increasingly difficult tasks by sensing and appropriately acting in a *real-world* environment.

We hope that the reader will find many motivating and enlightening ideas in the present collection. Our wish is that this book contribute to the development and further awareness of the new and fascinating field of evolutionary hardware systems.

We would like to thank the distinguished authors that contributed to this volume for their willingness to share the excitement of a new enterprise. We are also grateful to the Swiss Center for Electronics and Microtechnology (CSEM) and to the Computer Science Department at EPFL for financial support. Special thanks are due to Professor Daniel Mange, director of the Logic Systems Laboratory, for providing a constant source of energy and inspiration.

January 1996

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