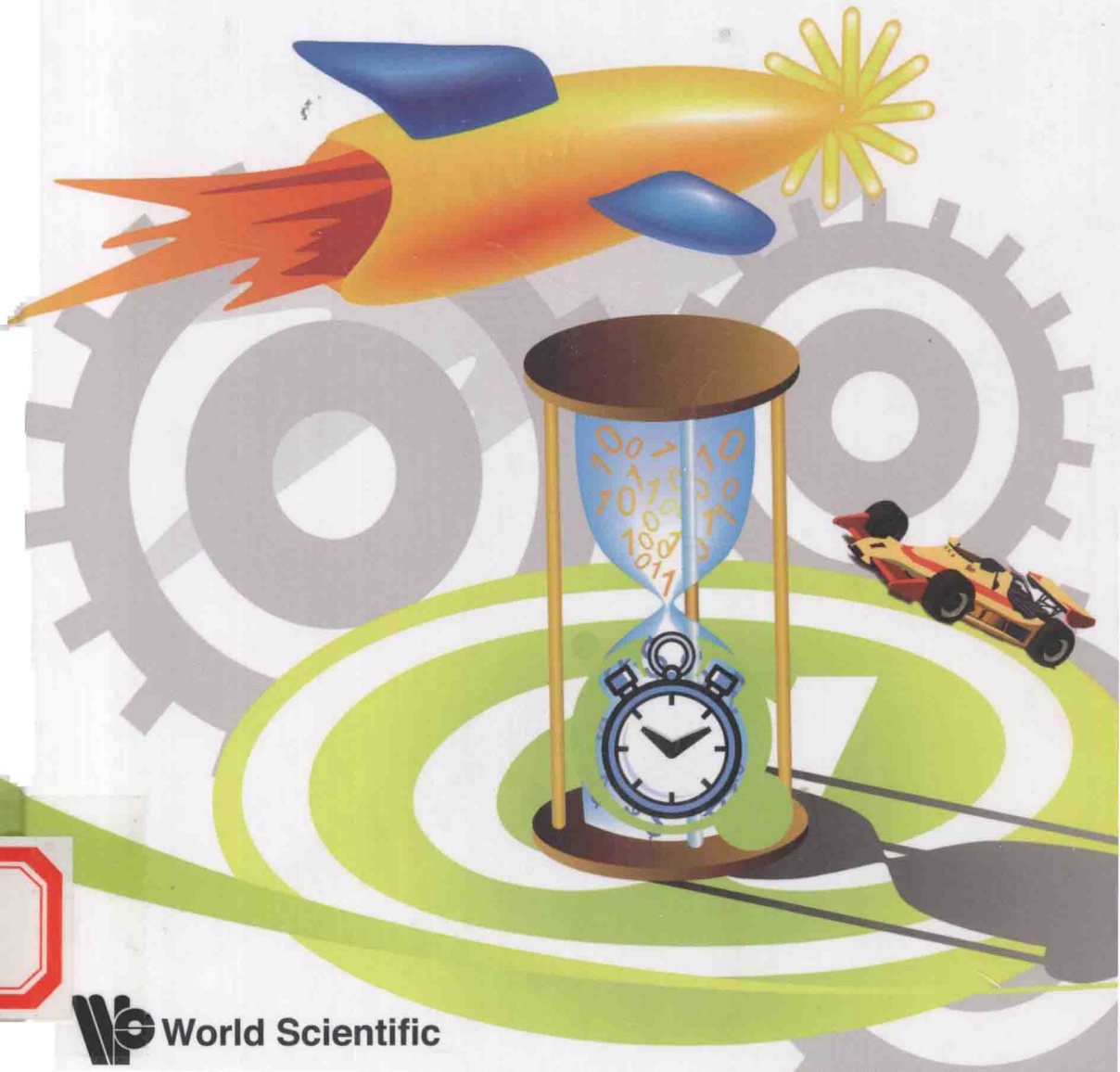
R K Shyamasundar • S Ramesh

Real Time Programming

Languages, Specification and Verification



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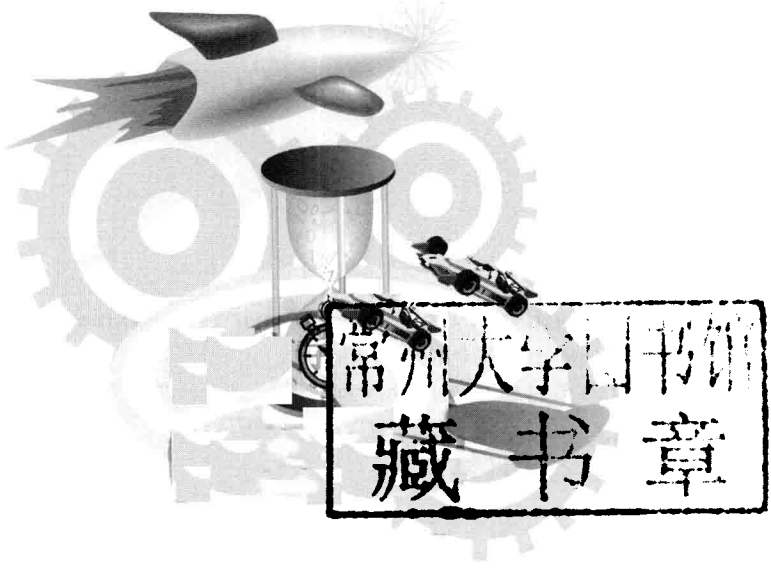

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REAL TIME PROGRAMMING: LANGUAGES, SPECIFICATION AND VERIFICATION

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Preface

The concept of process control has made *Embedded Systems* all pervasive. The applications range from home appliances (video pumps, cameras, set-top boxes, games), personal telecom and multimedia, medical therapy systems, process control systems, automobiles, avionics, tactical Control, nuclear industry etc. If one considers the processors by numbers or volume, it is of interest to note that only 1% of the total number of processors manufactured are used for general purpose computers (say desktop etc); the rest are all used in embedded systems. While general purpose processors is essentially a dedicated general purpose computational system, an embedded system is a complex system consisting of a package of hardware and software systems that can include a range of mechanical systems interfaced with the real-world to realize repetitive monitoring/actuating of the environment. Its' purpose is a dedicated function rather than general purpose computing. Hence, in embedded systems the focus is on the control logic that governs the interaction of the system with the real world. In other words, the challenges in the design of embedded systems lies in interfacing with the real-world meeting concurrent real-time constraints, and stringent safety considerations to augment component (sensor/actuator) interfaces. Thus, challenges towards the specification, design and realization of embedded systems can be summarized as follows:

1. Rigorous design and verification methodologies for embedded software. The grand challenge advocated by David Harel in this direction can be summarized as follows:

    - Devise frameworks for developing complex reactive systems providing means for describing and analyzing systems with the understanding that the structure be driven and propelled by *behaviour* of the systems. Needless to say tools play a vital role in the realization of such a dream.

2. Software Plays an important role in the design of embedded systems. A study shows that at least 60% of development time spent is spent on software coding. This has made a paradigm shift from hardware to software. This is also necessitated by the need to include late specification changes, shorter lifetime of embedded systems, and the need for the reuse of previous design functions independent of the platform. Thus, the main challenge is to invent design structures that match with the application domain. Developing a language independent platform to support such designs is another serious challenge.

In this book, we shall be focussing on the first goal.

Embedded control applications are concurrent and often real-time in nature: a controller runs concurrently with the physical system being controlled and is required to respond to the changes in the physical system state not only correctly but at the right times. For instance, a brake-by-wire subsystem of a car needs to brake the wheels of the car within a few milliseconds after detecting the pressing of the brake pedal. The development of real-time concurrent systems is many orders of magnitude more difficult than conventional data processing applications due to simultaneous evolution of concurrent components.

An emerging methodology of development of embedded control applications is *model-based development*. One of the main features of model based development paradigm is the use of models which are high level abstractions of software (and systems) and can be easily developed from requirements and are executable; the models can be automatically translated into low level code which can be mapped to target platform and integrated. Executable models help in early debugging of design leading to shorter and fast design cycle.

Synchronous programming methodology is one of the successful model based development methodologies of real-time embedded applications and hardware. This methodology was developed at around the same time by three French groups. An important feature of this methodology is a simplified and elegant abstraction of real-time: the synchrony hypothesis. According to this hypothesis, the reaction time of the controller implemented in software is zero. The validity of this assumption stems from the fact that the controllers are executed by powerful micro-controllers and processors which are quite fast compared to the slow physical system being controlled. The synchrony hypothesis greatly simplifies the design and verification of real-time systems as it reduces the number of interleaved executions of concurrent systems. Synchronous programs can also be efficiently translated

into low level code that can run on a variety of platforms. Recently these techniques have been commercialized into a number of tools that are being used in the aerospace and process control industries.

Spurred by the success of the synchronous methodology in many important industrial control applications, and due to the power and relative unawareness of this technology, we decided to devote this monograph to this methodology. In this monograph, we focus on the basic elements of synchronous methodology and include a detailed description of three synchronous languages: ESTEREL , Lustre and Argos.

Synchronous Languages are suitable for centralized, single processor and sequential applications. But many complex real-time embedded systems are often implemented over distributed platforms. Recently, the authors of the monograph have extended the synchronous methodology to such applications, developing modeling languages like Communicating Reactive Processes (CRP), Multi-clock ESTEREL and Communicating Reactive State Machines (CRSM). We discuss aspects of these formalisms and illustrate applications of the same.

Organization of the Monograph

The organization of the monograph is as follows. Chapters 1 - 4 discuss the general aspects of real time and reactive systems. Chapters 5 - 10 contain detailed descriptions of the ESTEREL language. While Section 5 gives in detail all the important constructs of ESTEREL , Chapter 6 gives a number of small case studies highlighting the features and tools of ESTEREL . Chapters 7 and 8 are concerned with advanced constructs of ESTEREL . Chapter 9 discusses a large case study in ESTEREL while the formal aspects of ESTEREL are given in Chapter 10. Chapters 11 - 12 deal with the other synchronous language, Lustre. While Section 11 introduces the features of Lustre, Section 12 discusses the modeling of Time Triggered Protocol in Lustre followed by a discussion of graphical language Argos motivated from Statecharts in Section 13. Chapter 14 discusses the verification methods used for ESTEREL and followed by observer based verification for Lustre.

While many reactive systems can be described using synchronous languages, large distributed applications demand a more flexible approach of combining both synchronous and asynchronous features. Chapter 16 introduces Communicating Reactive Processes (CRP), one of the earliest approach to combining synchrony and asynchrony. The semantic challenges of CRP is described in chapter 17 along with a formal semantics of CRP.

Chapter 18 discusses a pictorial variant of CRP, called Communicating Reactive State Machines Chapter 19 demonstrates how real time systems can be captured within the synchronous framework of ESTEREL . Multi-clock ESTEREL is a generalization the basic ESTEREL and is discussed in Chapter 20; multiclock ESTEREL permits modeling subsystems with different clocks. Chapter 21 summarizes the topics covered with a few important observations.

Dependence of the chapters

For the convenience of the reader, the dependence of the chapters are given below, where $a \rightarrow b$ denotes that Chapter b requires reading of Chapter a
$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9$
$5 \rightarrow 6 \rightarrow 10, 5 \rightarrow 11 \rightarrow 12 \rightarrow 13$
$7 \rightarrow 12, 5 \rightarrow 14, 5 \rightarrow 15, 11 \rightarrow 16$
$5 \rightarrow 17 \rightarrow 18, 17 \rightarrow 19, 5 \rightarrow 20, 5 \rightarrow 21$

The intended audience for the monograph include advanced graduate students and researchers interested in synchronous languages and embedded software engineering; practicing engineers involved in embedded software development would also benefit from the book. The monograph would also provide useful material for part of a graduate course on embedded systems.

Acknowledgement

It is great pleasure to thank the inventors of synchronous languages ESTEREL (Gerard Berry), LUSTRE (Paul Caspi, Nicolas Halbwachs), SIGNAL (P. Le Guernic , Albert Benveniste), Statecharts (David Harel, Amir Pnueli), and ARGOS (Florence Maraninchi), with whom the authors had close collaborations and discussions. We also thank the Synchronous Programming Community (the authors have gained a lot in their participation in the yearly Synchronous Programming Workshops) with whom we have had a long association.

The major part of the work was done while the authors were with Tata Institute of Fundamental Research, Mumbai, and Indian Institute of Technology Bombay, Mumbai respectively. We gratefully acknowledge the generous support of these Institutions. Many of the joint works in the area came through the projects under Indo-French Centre for Promotion of Advanced Research (IFCPAR), New Delhi. It is pleasure to thank IFCPAR for the generous support. Professor R.K. Shyamasundar thanks IBM India Research Lab., New Delhi, with which he was affiliated during 2005-2008 and Prof. S. Ramesh thanks India Science Lab General Motors R&D Bangalore, with which he is currently affiliated, for the support and permission to use the resources towards the finalization of the material.

Thanks go to a large number students and collaborators who worked with us. Specially we thank Basant Rajan, Tata Institute of Fundamental Research who mainly worked and developed the multiclock Esterel. A special thanks goes to K Kalyanasundaram who developed and tested examples on Lustre and TTP, and Prahladavaradan Sampath, General Motors R&D Bangalore for reading the entire draft and giving very useful comments that improved the presentation of the monograph.

The authors would like to express their sincere appreciation for the patience and understanding shown by the publishers without which this monograph would not have seen the light of the day.

Contents

Part I: Real Time Systems: Background

Summary

In the next four sections, we shall provide (i) an overview of the general characteristics of real-time systems and reactive systems, (ii) a general discussion on formal development methodologies for real-time systems, (iii) characteristics of real-time languages and (iv) programming characteristics of reactive systems and the synchrony hypothesis.

Chapter 1

Real Time System Characteristics

Real-Time systems are designed to cater to many applications ranging from simple home appliances and laboratory instruments to complex control systems for chemical and nuclear plants, flight guidance of aircrafts and ballistic missiles. All these applications require a computational system (including both the computer and software) interacting with physical equipments like sensors and actuators. Such systems are often referred to as *embedded systems*.

An important feature of many of these systems is the ability to provide *continual* and *timely* response to unpredictable changes in the state of the environment. Hence, these systems have relatively rigid performance requirements. Further, these systems have to satisfy stringent *fail-safe* reliability requirements as failure in many of the applications will result in economic, human or ecological catastrophes. For these reasons, these systems are called *safety-critical* or *time-critical* systems.

In general, the interface between a real-time system and its environment tends to be complex, asynchronous, and distributed. This is due to the fact that the environment of the system consists of a number of physical entities that have autonomous behavior and that interact with the systems asynchronously; it is probably the complexity of the environment that necessitates computer support in the first place. Such systems can be extraordinarily hard to test. The complexity of the environment interface is one obstacle, and the fact that these programs often cannot be tested in their operational environments is another. It is not feasible to test flight-guidance software by flying with it, nor to test ballistic-missile-defense software un-

der battle conditions. In summary, some of the important characteristics of real-time systems are:

- The environment that a system interacts with, is highly nondeterministic and often consists of asynchronous distributed units; there is no way to anticipate in advance the precise order of different external events.
- High speed external events may affect the flow of control in the system easily.
- Responses to external events should be within strict bounded time limits.
- They tend to be large, complex and extraordinarily hard to test.
- In some real time applications, the mission time is long and the system, during its mission time should not only deal with ordinary situations but also must be able to recover from some exceptional situations.

In view of the above characteristics, the design of real-time systems poses serious challenges. There is a definite need for systematic methods and methodologies for designing them. In the design of quality software, high level programming languages and abstract models have a major role to play. The focus of this monograph is on some of the high level programming abstractions that have been found to be useful in designing provably correct real-time programs.

1.1 Real-time and Reactive Programs

There are many dichotomies of programs such as determinism/non determinism, synchrony/asynchrony, off-line/on-line, virtual time/ real-time, sequential/concurrent. However, depending on the way they interact with their environment, programs can be classified into the following three broad kinds[9]:

1. *Transformational Programs:* These programs compute outputs given the input; programs interact with their environment once at the beginning to get inputs and once at the end to give outputs. Compilers are examples belonging to this category.