Preface

Distributed control and embedded systems (*DCESs*) incorporating real-time control and communication functions implemented on some appropriate distributed *Hardwareare/Software dedicated architecture* are ubiquitous in areas of avionics, automotive, production of energy, space exploration and many others. It would be impossible to run the existing nuclear plants with the current level of safety requirements without their presence. Furthermore, *DCESs* appear to be essential to send robots exploring space, shuttles and satellites orbiting the earth. Our cars are more fun to drive, safer and cleaner, thanks to small embedded computers that perform functions such as cruise control, navigation system, *ABS*, *ESP*, airbag, optimal control of injection and many others and which exchange information between them in real-time. The quality of their design is directly related to the quality, performance and security of the final products (planes, cars, ...) and they directly influence the results of the related companies. This can be explained by the fact that the strong constraints of mass production imply a greater sensitivity on the prices of embedded computers and communication components. Requirements in terms of quality and performance of new products not only involve new methodologies and tools for designing of *DCESs*, but also imply a better use of resources they offer. Finally, the competition in which companies are involved forces engineers to design more efficient products that are, more and more complex, less expensive and with shorter design and production times than the competing firms.

To address these scientific and technical challenges, methodologies and design tools for *DCESs* are proposed by different teams of researchers and engineers according to their own scientific cultures. The proposed methods as well as the modeling and implementation tools are mainly based on the model of computation, discrete or continuous, and often involve computer science or control systems researchers and engineers. The results obtained so far have justified this scientific dichotomy which is nothing more than a view on the same object with discrete and continuous dynamics, commonly known as Hybrid Dynamic Systems (*HDS*). In the 1990s, several projects offering modeling, design and verification tools of *HDS* have emerged (*HyTech* [230], *Ptolemy* [229], UPPAAL [239], *KRONOS* [127], *HYSDEL* [228] ...). Experiments on these tools showed that the way to handle the *model* *complexity* is essential in the design and verification of *DCESs*. The pragmatic approach involving a thorough knowledge of the model is essential in managing the complexity and therefore in the design and verification of *DCESs*.

Other tools for *DCESs* design, specially related to calculation models, have been developed up to now. In the field of real-time systems, modeling and code generation tools such as *SCADE* [128], *SynDEx* [129] … continue to be developed. They are used to model the temporal aspect of control tasks according to the dynamical characteristics of the objects to check, to generate real-time code on various targets and to elaborate the verification of different properties. This diversity of tools is explained not only by the existing competition but also by the importance that each particular view of a *HDS* has in the design. It does not only highlight a problem of training and scientific culture of our engineers and designers but also the importance that a particular view has in the life cycle of an *HDS*. At the same time, this fact reveals that current paradigm of computer science does not necessarily apply to embedded systems, as underlined by *Henzinger and Sifakis* in [116], and even more to *DCESs* design which has to be completed by a control system and signal processing view. In our opinion, a holistic approach and methodology for the design of *DCESs* which integrates consistently the essential paradigm from control theory, computer science and signal processing is of great actuality operating a necessary convergence toward the study of *DCESs*.

From the system control point of view, a fundamental question that determines the balance is whether the *DCESs* can be more efficient than their counterparts based on a centralized architecture and if this is the case, the price to be paid needs to be evaluated. There are at least three criteria which help answering to such a question. The *first* criterion relates to the nature of time-delays generated by each architecture. Surprisingly, the delay, can be more problematic in the case of centralized architecture. The *second* criterion concerns the existence of appropriate design tools. Concerning the existing design tools, in our opinion, we are at the beginning of a long road. Finally, the *third* criterion is related to the reliability and scalability. Naturally, distributed architectures are more reliable and scalable due to the distribution of their computing resources. Increasing or modifying the number of networks nodes and the number of real-time tasks to be executed on each of them may be done also dynamically. Moreover, if we observe the deployment of real-time networks operated since the arrival of the *Control Area Networks* (*CAN*) buses (in its standard version, by the middle of 1986) in various products such as cars, aircrafts, trains, … and combined it with the actual scientific and technology development in the field allows thinking that we are at the beginning of a movement towards a generalization of distributed *Hardware/Software* (*HW/SW*) architecture in which different network nodes share their information and computing resources. Naturally, this requires a thorough understanding of real-time communication and computing phenomena in order to construct relevant and reduced complexity/order models. These models should represent accurately the temporal properties of states and control signals to enable their integration in the design of control laws and thus ensure the desired performance of *DCESs*.

In this monograph, several results on joint design of control laws and scheduling algorithms as well as stability analysis of some special cases of *DCESs* including, among others, the study of the effects induced by the delays are presented. This study is addressed by considering different aspects of the limitations imposed by the use of communication channels as well as embedded node processors composing the *HW/SW* architecture of *DCESs*. We specially focused on limitations in terms of network communication bandwidth and processor calculation power inducing sampling and period jitter, communication delay and signal quantization limitation. In our opinion, this approach of *DCESs* control allows to better emphasize on optimal use of its computing and communication resources. The algorithms used to solve the joint design of optimal control laws and message communication and/or real-time task scheduling have *NP-complete complexity*[1] [37, 93]. Reducing their complexity requests a deeper study of their models and their stability with respect to the delays induced by both signal communication between nodes and those induced by the real-time task scheduler at each node. We observed two interesting results in the stability study of *DCESs*. *First*, their stability, in some special cases, represents some unexpected behaviors with respect to the standard intuition. An increase in the input/output delay does not necessarily imply a potential destabilization of the system. This is in line with the design goal of reducing the computational and communication resources by guaranteeing the same level of *DCESs* performance. *Second*, it is not necessary to satisfy the stability conditions for each sampling period. Thus, we can handle and control the temporal expression of input/output delays allowing the design and implementation of optimal controllers for *DCESs* satisfying communication and calculation constraints.

The objectives and the structure of this monograph are different with respect to those proposed in two excellent books [124] and [17]. We try to construct a unified approach of the analysis and design of *DCESs*. The approach of the networked control systems design presented in [100] appears to be quite close to our methodology of design of *DCESs*. However, the major difference lies in the modeling and the switch control design to handle the induced delay and especially in the way it is taking into account concurrent calculation of control signals and their time scheduling.

As mentioned before, we focus on the optimal design of *DCESs* with respect to the communication and calculation resources constraints as well as the design of special control algorithms based on the analysis of induced time-delay system. In this context, a particular emphasis is put on the optimal control signals scheduling based on the systems state. In order to render this complex optimization problem feasible in real-time, a time decomposition is operated based on periodicity induced by the static scheduling. It is natural that our approach in the design and analysis of *DCESs* can not cover all the classes of *DCESs* which appear to be extremely rich and various. We do not claim either to give the best methods and tools in the optimal design and analysis of *DCESs* whose solution depends on the particular nature of each of them. We believe that the co-design approaches which consist in the synthesis of the optimal control laws and the generation of an optimal scheduling of control signals on the real-time network based on a thorough analysis of the

[1]NP-complete is the set of all decision problems whose solutions can be verified in polynomial time.

induced time-delay system have the best chances to render this problem feasible and to find optimal or some sub-optimal solution.

Book Outline and Content

This book is organized in three parts. In *Part* I, composed of the first three chapters, a general overview, the state of art as well as the description of an abstract model of *DCESs* are given. In *Part* II, the problem of optimal co-design of *DCESs* is addressed under calculation and communication constraints focusing more on the scheduling of control signals on the networks as well as on the scheduling of control tasks on the *DCES* nodes. Finally, in *Part* III composed of four chapters, a particular attention is paid to various control configuration strategies as well as to the effects induced by delays (constant or time-varying) on the overall system's stability.

The main contributions are summarized as follows:

- *Optimal integrated control and scheduling of resource-constrained systems:* We start by adopting a model introduced by [122], where control and communication resource allocation aspects are strongly dependent. By interpreting such a model as a hybrid dynamical system *HDS* [21] with two types of inputs: *control inputs* and *scheduling inputs*, we formalize and solve the problem of the joint optimization of control and scheduling, by using an appropriate quadratic cost function as a performance criterion. The study of the properties of the optimal schedule, through some selected illustrative examples, shows that it is strongly dependent on the *DCES* state and dynamics. This dependence offers some ideas for improving *DCESs* performances using on-line scheduling algorithms based on their state information. However, this dependence shows that it is necessary to find appropriate performance metrics for the synthesis of optimal off-line schedules.
- *Optimal integrated control and off-line scheduling in the sense of the $\mathcal{H}_2$ norm:* In the context above, we motivate the use of the $\mathcal{H}_2$ norm [14] as a design criterion for obtaining optimal off-line schedules that only depend on the intrinsic characteristics of the system. We propose a method for the joint control and off-line scheduling in the sense of the $\mathcal{H}_2$ criterion. We show that this problem can be decomposed into two sub-problems, that can be solved separately. The first sub-problem aims at determining the optimal off-line scheduling in the sense of the $\mathcal{H}_2$ criterion and can be solved by applying the so-called *branch and bound* method [85, 86, 146]. The second sub-problem aims at computing the optimal control gains and can be solved by adopting tools from optimal control theory of periodic systems [45].
- *The use of the model predictive control as a means for the joint optimal control and on-line scheduling:* We propose an approach that allows on-line calculation of the optimal values of both control signals and scheduling decisions, in the sense defined by an appropriate quadratic cost function. This approach relies on the use of the model predictive control (*MPC*) technique [50], which was applied successfully in the past for the control of *HDS* [21]. We illustrate the performance

improvements, in terms of quality of control, which are brought by this approach, compared to static approaches, where the used scheduling is pre-computed off-line. We also state some appropriate stability conditions of the corresponding predictive controller.

- *Optimal integrated control and on-line scheduling of resource-constrained systems:* The major drawback of the model predictive control technique is that it requires solving an optimization problem which is of *NP-complete* [37] type. For that reason, an on-line sub-optimal scheduling algorithm, called *OPP* for *optimal pointer placement* is proposed. While being based on an off-line pre-computed optimal schedule, *OPP* makes possible to allocate on-line the communication resources, by taking into account the state of the controlled dynamical systems. It is shown that, under mild conditions, *OPP* ensures the asymptotic stability of the controlled systems and enables in all the situations the improvement of the control performance compared to the basic static scheduling. Furthermore, *OPP* is applied to two typical examples of a distributed control and embedded systems: the car active suspension controller [27] and the control of a quadrotor.
- *Optimal relation between quantization precision and sampling rates:* We extend the model that was first considered in order to take into account quantization related aspects [72]. Consequently, the communication constrains are modeled at the bit level, in bits per second. In general, increasing the sampling frequency improves the disturbance rejection abilities whereas increasing the quantization precision improves the steady state precision. However, when the bandwidth is limited, increasing the sampling frequency involves the reduction of the quantization precision. As the opposite, augmenting the quantization precision requires the lowering of the sampling frequency. Based on these observations, we propose an approach allowing the dynamical on-line assignment of sampling frequencies and control inputs quantization [24]. This approach based on the model predictive control technique enables to choose the sampling frequency and the quantization levels of control signals from a predefined set, in order to optimize the control performance.
- *Optimal state-feedback resource allocation:* A new approach for the co-design of control and real-time scheduling is proposed. This approach decomposes the problem into two sub-problems solved separately. The first sub-problem amounts to find the optimal non-preemptive off-line schedule, and can be solved by using the *branch and bound* method [85, 86, 146]. The second sub-problem resolution makes use of the lifting technique [45] to determine the optimal control gains, based on the solution of the first sub-problem. In the second part, a plant state feedback scheduling algorithm, called reactive pointer placement (*RPP*) scheduling algorithm is proposed. Its objective is to improve the control performance by reacting fastly to unexpected disturbances. Performance improvements as well as stability guarantees using the *RPP* algorithm are formally proven and then illustrated on a comprehensive implementation model, which was simulated using the tool TRUETIME [5]. Finally, the *RPP* algorithm is implemented on an embedded processor in order to achieve the concurrent real-time speed regulation of two DC motors.

- *Insight in delay system modeling of* DCESs*:* The *DCESs* stability and performance robustness depend on the model of communication and calculation applied to the associated *Hardware/Software* application architecture and related scheduling policy of state/control communication messages as well as of control tasks based on system state. The scheduling policy organizes the distribution of communication and calculation resources between competing nodes and tasks and handles contention situation. As it will be seen throughout this document, the sampling period of sensor and actuation signals update as well as execution of related control task will vary with time. This phenomenon induces variable delays in the *DCES* whose time characteristics, strongly conditions their performance. In this context, we propose and briefly discuss various delay models that can be used for representing *DCESs*.
- *Stability analysis of* DCESs *subject to induced delays:* We analyze some possible scenarios or time-delay models based on the off-line periodic and on-line aperiodic scheduling. We have to point out the fact that the control signal scheduling on the network as well as control tasks scheduling on each *DCES* node are non preemptive ones. The objectives of this analysis are twofold: *first,* to obtain less conservative stability domain with respect to the network delay and sampling period variation, and *second*, to shed some light on the interplay between resource allocation and system stability and performances. In some special cases, we observe a contradiction with the generally accepted intuition which consists in the fact that more computation or communication resources will easily stabilize a given *DCES*.
- *Design of the hyper-sampling sequence of* DCESs*:* Optimal scheduling of a number of control tasks on a processor or sensors and actuators signals on a real-time communication network depends mainly on the relative dynamics of the related subsystems composing a *DCES*. More a given subsystem dynamics is important, more it needs calculation and/or communication resources. As it will be seen in Chap. 2, the scheduling chronograms are periodic and their period depends on relative dynamics of the sub-systems sharing the given resource. Generally, such a period is called *hyperperiod* or *hyper-sampling period*. In Chap. 11, we propose a new method to optimally design the *hyper-sampling period* (including the standard single-sampling period as a special case) for *DCESs*. Furthermore, we will develop an analytic relation between the dynamic performance index and the *hyper-sampling period*. Thus, given an *average sampling frequency*, we will be able to design optimally the *hyper-sampling period* corresponding to the minimum value of dynamic performance index.
- *An optimal control strategy for distributed control and embedded systems:* Enhancing the stability as well as dynamic performances of some special class of *DCESs* using switched sampled-data (*SD*) control strategy is also studied. Regarding the stability issue, we will show that the use of the switched *SD* control strategy allows to enlarge the stability bound on the sampling period. In order to take into account the inter-sample behavior, we choose a continuous-time cost function to evaluate the system performances. It will be seen that the performance index can be explicitly calculated as a function of the switching time-parameter

and the optimal value of the performance index can be analytically found. Another advantage of the applied approach consists in analyzing standard control systems problems and more specifically in the definition of their optimal sampling period. The results obtained clearly show that increasing the sampling period does not necessarily reduce the system's performances. This phenomenon is quite interesting since it allows us, in some cases, increasing the sampling period or reducing the computational resources and achieving simultaneously better system's performances.

- *Optimal design of switched hold-zero compensation strategy for* DCESs *subject to control missing:* The admissible control input missing rate (*ACMR*) of some sampled-data *DCESs* is an important index which reflects the stability robustness with respect to control input missing induced by packets dropout or induced delays. We propose a simple switched hold-zero (*HZ*) control law as a control-missing compensator. More precisely, the switched *HZ* control has two control modes: the hold-control and the zero-control, respectively. The switching between two control modes is determined by an appropriate switching parameter. To obtain an *ACMR* as large as possible, we present a method to optimally design the corresponding switching parameter. It will be seen that the switched *HZ* control leads to better results than both the zero-control and the hold-control strategies acting separately and independently. In addition, the *ACMR* index can be used to calculate an hyper-period of messages scheduling optimizing the network bandwidth.

This book is mainly addressed to post-graduated students willing to operate research studies on *DCESs* and especially on the optimization of their performances with respect to communication and calculation resources. In our opinion, the modeling and analysis tools given in this monograph may be useful for research engineers in modeling and analyzing of *DCESs* for industrial applications purposes. Finally, the design methodology combined with complexity reduction objectives may help them to consistently formulate the corresponding *DCESs* design problem. The principal concepts and the methods are introduced and explained via some concrete illustrations and examples borrowed from robotics, automotive application and unmanned aerial vehicle (*UAV*).

How to Read the Book?

This monograph can be read in different ways depending on the proximity of the reader with the subject. The first part is necessary if the associated calculation and communication model of *DCESs* are, in large part, unknown to them. The proposed models are simple and general enough allowing to integrate them easily in the design of control and scheduling algorithms of *DCESs*. A structural reading of the second part allows to understand the general idea of the proposed approaches. Naturally, a more informative reading where the methodological aspect is complemented by implementation of concrete examples is also possible, and even recommended, paving the way for real-world and/or industrial applications. Concerning the third part of this document, except the ninth chapter, where we give a number of induced input delayed models of *DCESs*, the other chapters can be read independently.

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