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Full Length Article

Petri nets and Automatic Control: A historical perspective☆

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ABSTRACT

The goal of this paper is to overview the historical development of the field of Petri nets (PNs) from a Systems Theory and Automatic Control perspective. It is intentionally not meant to be comprehensive: we limit ourselves to outline, through selected representative topics, some of the conceptual issues studied in the literature. In a first part we retrace the emergence of some basic net concepts to provide a broad view of the family of PN formalisms. Then we focus, more specifically, on the use of Petri nets within Automatic Control. Discrete net models have been considered since the middle of the 70s and starting since the late 80s have also been used for addressing classical problems, such as supervisory and deadlock control, state estimation, diagnosis, and so on. The double benefit is the ability to model a larger class of systems and to provide efficient algorithms for solving certain of those problems. We also discuss new approaches based on continuous and hybrid nets, which have been developed within the Automatic Control community.

1. Preliminary overview

Born in a Computer Science milieu, as Carl Adam Petri was fond of saying, nets belong to the broad domain of *Systems Theory*. In the late fifties and at the beginning of the 60s of the past century, when the main focus was on local computations of mathematically intricate sequential problems, Petri developed a fresh approach to the theory of *concurrency* and *synchronization*. In fact, the title of his seminal work (Petri, 1962) is expressive: *Communication with Automata.*[1] Considering notions of *dependence* and *independence* of actions, *locality* of states and events were straightforwardly captured to support both *temporal realism* and *top-down* and *bottom-up* modeling approaches for concurrent-distributed Discrete Event Systems (DES).

Petri Nets (PNs) are bipartite valued graphs: *places* and *transitions* are the nodes and *weights*—inscriptions, more in general—are assigned to arcs. Their dynamics derives from the *marking* or distributed state.

At the beginning, PNs were purely *autonomous* models, meaning by that *untimed* or, more precisely, possessing only a *qualitative* notion of time based on event ordering: earlier or later, possibly at the same time. Also they were *nondeterministic* models, a humble position leading to their logical study by considering all possible evolutions. The inception of *quantitative* time dates to the mid-70s, when issues related to performance evaluation, verification and control, such as throughput computation, optimal scheduling, etc., started to be considered. The works by Ramchandani (1973), Merlin (1974) and Sifakis (1977) are a few examples of representative early proposals for endowing PNs with a quantitative time structure. In this sense PNs are *semi-interpreted*, i.e., there exist several "extended" or "interpreted" formalisms, suited to deal with diverse purposes but sharing the basic common principles. For example, beyond the above mentioned timed formalisms, one may associate input and output events with the firing of transitions to define *marking diagrams* (also *synchronized PNs*), which represent a clear generalization of Mealy or Moore machines in which the global state is replaced by a distributed one.

The above mentioned diversity of formalisms turns PNs into a theoretical framework or *paradigm* for the modeling of DES along their *life-cycle* (Silva & Teruel, 1996), well suited to deal with the formal representation and development of systems from preliminary design to performance evaluation and control, even including fault-tolerant implementation and operation. In particular, for a given system, this means to be able to check purely *logical* properties (such as boundedness, deadlock-freeness, liveness or reversibility in autonomous models), to compute *performance* properties (such as average values for: throughput of a subsystem; marking or queue length of a place; or utilization rate of a resource),

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[1] For its translation into English (Petri, 1966).

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to derive good *control* strategies (for example to minimize a makespan or to decide an optimal production mix), etc. In other words, a *modeling paradigm* is a conceptual framework that allows one to obtain modeling *formalisms* from some common concepts and principles with the consequent *economy, coherence* and *synergy*, among other benefits.

As an example of synergy, we want to explicitly mention the computation of the *visit ratio* of transitions in a stochastic PN, which naturally leads to state some necessary or sufficient conditions for its liveness as autonomous. Following the seminal work by Campos, Chiola, and Silva (1991), a broader perspective of so called *rank theorems* is provided by Silva, Teruel, and Colom (1998).

The first broad and organic perspective of works related to PNs is due to Brauer (1980). It integrates the "structural" line deriving from Petri first proposal and the "automata-language" based approach,[2] together with *Vector Addition Systems* (Karp & Miller, 1969) and other graphical models for parallel computations, independently introduced in the USA since the late 60s. From 1984 and for almost two decades, a significant part of the core of contributions to PN theory and applications was edited by Grezgorz Rozenberg in the series *Advances in Petri Nets*, published in the Lecture Notes in Computer Science (LNCS). Most of those contributions came from Computer Science.

Although with different degree of centrality, the family of formalisms known as Petri nets have spread from Computer Science and Engineering (CSE) to other domains, including Automatic Control (AC) and Operations Research (OR), always supported by a solid background in Mathematics and Logic. We focus in this work mainly on the AC domain. Thus what is here presented is naturally a partial/biased view of the entire PN field. For a broader historical perspective which traces the development of PN theory and applications in parallel with that of the PN community, see Silva (2013). The AC control community started discovering PNs in the middle of the 70s. For example, Moalla, Sifakis, and Silva (1980), following the spirit of the times, use them for modeling, verification, analysis and implementation (hardwired, microprogrammed and programmed) of *logic controllers*.

Although the long period that has elapsed since 1962 has seen the appearance of an impressive number of contributions, a significant number of fundamental problems is still open. The impact of PNs on information technology can be assessed considering the conferences, courses, books, tools or standard norms (IEC, ISO, etc.) devoted to them (Fig. 1). Applications of PN theory and methods exist in an extremely broad number of fields, among others: manufacturing, logistic, computer hardware and software, protocols engineering, traffic, biochemistry, population dynamics or epidemiology, for example.

In the 80s the quantitative notion of time generated a first "transient schism" (or divergence) in the PN community among those researchers accepting quantitative timed interpretations in PNs versus those rejecting them. Moreover, in the endless fight against the well-known *state-explosion problem* that affect DESs, new variants such as *continuous* or *fluid* and *hybrid* PNs, were introduced by the end of the 80s: this lead to a new scientific controversy in the PN community of the times. The main argument against the new class of formalisms was that "real" PNs must be discrete models! In some sense, at the end of the past century and the beginning of the present one—in parallel with the rising interest of the AC community in DESs—this generated a second "transient schism" in the community among those researchers accepting particular fluid relaxations of PNs as "approximated" models for DES versus those rejecting them. Even if we speak of "transients schisms", the modeling paradigm was always flexible enough to integrate the many "extensions" that do not contradict the basic concepts of PNs: bipartition, locality, consumption/production logic, etc.

Fig. 1. The University of Zaragoza granted Carl Adam Petri an honorary doctorate on April 15, 1999. The award was conferred during the celebrations the 25th anniversary of the foundation of the Engineering School (previously Centro Politécnico Superior). The picture was taken after the ceremony, on the central staircase of the Paraninfo building, and shows representatives of research teams from Australia, Canada, France, Italy, Spain and United Kingdom.

This paper is a revised and enlarged version of Giua and Silva (2017), with additional discussions throughout and the inclusion of new sections on "early books" in the field and on scheduling; it also contains an appendix providing a collection of bibliometric data about the development of the field. It is structured as follows. In Section 2 the emergence of basic concepts is recalled and we are able to explicitly bring to the attention the family of PN formalisms as a modeling paradigm. Section 3 reviews some of the first books devoted to Petri nets, which have been instrumental in creating a sense of community. Section 4 deals with the use of PNs as dynamical models to address classical problems of AC, such as control, state estimation, diagnosis, scheduling, etc. Section 5 aims to sketch a bridge connecting control theory and engineering of continuous, hybrid and discrete event systems. Section 6 mentions a few of the topics that we could not properly describe in depth in this paper. Finally a few promising areas that are open to future research are briefly discussed in Section 7, followed by the above mentioned Appendix.

2. Petri nets: from basic concepts to the modeling paradigm

Due to space limitations, just a few key steps in the long development of Petri net models are discussed in the sequel, starting with the seminal work of the field (Petri, 1962). In contrast with a widespread common vulgata, in the thesis of Petri there exists no PN in its classical graphical notation, something that appeared some three years later. In 2007 Petri confessed that

> the graphical representation of structural knowledge which is now in widespread use I invented it in a playful mood in August 1939, and practiced it intensively for the purpose of memorizing chemical processes, using circles for substances and

[2] Carl Adam Petri persistently claimed that formal languages (in the automata theory sense), were not appropriate to deal with the expressiveness of net systems models. In fact, their sequentialized views (sequences of events/occurrences of transitions) does not explicitly provide information about concurrency and distribution of the modeled system. Informally speaking, some kind of "isomorphism" between the described system and the model contribute to the "faithfulness and understandability" of those formal constructions.