Modeling, analysis and control of Discrete Event Systems: a Petri net perspective

Alessandro Giua†, Manuel Silva‡

† Aix Marseille Univ, Université de Toulon, CNRS, ENSAM, LSIS, Marseille, France (alessandro.giua@univ-amu.fr) and DIEE, University of Cagliari, Italy (giua@d.iee.unica.it)
‡ University of Zaragoza, Spain (silva@unizar.es)

Abstract: The goal of this contribution is to briefly overview the historical development of the field of Petri nets under a System Theory and Automatic Control perspective. It is by far not meant to be comprehensive or inclusive, but to review through several representative areas a few of the conceptual issues studied in the literature. It was not possible to consider here the many domains of application were the Petri Nets modeling paradigm was used, among many others: manufacturing, logistic, hardware and software, protocols engineering, health management, transportation, etc.

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1. PRELIMINARY OVERVIEW

Born in a Computer Science milieu, as Carl Adam Petri was fond of saying, nets belongs to Systems Theory in a broad sense. In the late fifties and beginning of the sixties of the past century, when the main focus was on local computations of mathematically intricate sequential problems, Petri developed a fresh approach to the conceptualization of concurrency and synchronization. In fact, the title of the seminal work of the field (Petri, 1962) is expressive: Communication with Automata. Considering notions of dependence and independence of actions, locality of states and events were straightforwardly captured allowing 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 only autonomous, meaning by that untimed or, more precisely, possessing only a qualitative notion of time: earlier or later; possibly at the same time. Also they were non deterministic models, a humble position leading to their logical study by contemplating all possible behaviors. The introduction of quantitative time dates to the middle of the seventies, when topics related to performance evaluation, verification and control, such as throughput computation, optimal scheduling, etc., started to be considered: Ramchandani (1973); Merlin (1974) and Sifakis (1977) are a small subset of representative early works on PN with time. 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 many timed proposals, associating certain types of external events with the firing of transitions, marking diagrams (also synchronized PNs) constitute a clear generalizations of Moore or Mealy machines, in which the global state is substituted by a distributed one.

The above mentioned diversity of formalisms turns PNs into a conceptual framework or paradigm for the modeling of DEDS along their life-cycle (Silva and Teruel, 1996), allowing 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), to derive good control strategies (for example to minimize a make-span 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 an stochastic PN, allows to state some necessary or sufficient conditions for its liveness as autonomous. Campos et al. (1991) is the seminal work; a broader perspective of so called rank theorems is provided in Silva et al. (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, together with Vector Addi-

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 “isomor-
This paper is structured as follows. In Section 2 the consumption/production logic, etc. contradict the basic concepts of PNs: bipartition, locality, etc. The AC community in DESs. Even if we speak of “transient schism” between the described system and the model contribute to the “faithfulness and understandability” of those formal constructions. For an historical perspective approaching a broader view on the development of the theory and its applications, together with elements of the development of the PN community, see (Silva, 2013).

2. PETRI NETS: FROM BASIC CONCEPTS TO THE MODELING PARADIGM

Due to space limitations, a very restricted subset of steps is traced in the sequel, starting with the seminal work of the field (Petri, 1962). In contrast with a widespread common vulgata, in this work 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 squares for reactions, interconnected by arrows to denote IN and OUT”. The reason for this explicit omission was that he “did not want the theory to appear as a graphical method instead of a mathematical attack on the then prevailing Automata Theory, based on arguments taken from modern Physics”. The first net based formalism became what is known as Condition/Event nets, that are ordinary and 1-safe by definition. Its generalization to the more common Place/Transitions nets (PT-nets, most frequently simply denoted as PNs) happened during the second half of the sixties, appearing in the same years in the related works of the teams lead in the USA by Anatole Holt (working in private company) and by Jack B. Dennis (project MAC at MIT). Holt gave the name of “Petri Nets” to this class of formalisms. It was at this time that the fundamental differences between automata and PT-net systems (in the sequel simply PNs) were established. The most striking is the fact that while automata are characterized by a global symbolic state, in PNs the state is distributed and numerical. A place is a local state variable whose value (i.e., the marking) is a nonnegative integer, while a transition represents a local event whose occurrence changes the value of a subset of places. Moreover, the marking evolution logic is a non-monotonous consumption/production logic which straightforwardly allows the modeling of unbounded (non-finite) state spaces, and of the use of resources. As a consequence, concurrency (simultaneously enabled transitions that are not in conflict) and synchronizations (through joins or rendez-vous), can be naturally modeled. Therefore, stated from a different perspective, it can be said that cooperation and competition relationships can be directly represented.

The locality of places and transitions (and their duality) allows concurrent-distributed DES to be modeled interleaving in a free way top-down and bottom-up approaches. Differently stated, models can be constructed by refining transitions or places; also by composing modules through transitions (synchronizations) or through places (fusions), with the advantage that in any case the structure of modules is preserved.
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