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Conference Paper · July 2016

Thushara Ekanayake
Uva Wellassa University

Prasad K. D. V. Yarlagadda
Queensland University of Technology

Shirley Devapriya Dewasurendra
University of Peradeniya - retired

Sunil Gamini Abeyratne
University of Peradeniya

Proceedings of 2016 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE 2016)
2016 World Congress on Engineering Asset Management (WCEAM2016)
July 25-28, 2016, Jiuzhaigou, Sichuan, China

QR2MSE2016 & WCEAM 2016-DRAFT

Model Based Fault Diagnosis and Prognosis of Dynamic Systems: A Review

Thushara Ekanayake[1], Prasad Yarlagadda[2], Devapriya Dewasurendra[3], Sunil Abeyratne[3], Lin Ma[2]

1. Faculty of Science and Technology,
Uva Wellassa University,
Badulla, 90000, Sri Lanka
2. Faculty of Science and Engineering,
Queensland University of Technology,
Brisbane, 4000, Australia
3. Faculty of Engineering,
University of Peradeniya,
Peradeniya, 20400, Sri Lanka

ABSTRACT

In maintenance of engineering systems, condition monitoring, fault diagnosis and fault prognosis constitute some of the principal tasks. With the increase of the number of machines within processing plants and their operational complexities, many engineers and researchers have started looking for automated solutions for these tasks. In most of the proposed solutions, these dynamic systems are modelled using tools like automata, Petri nets, bond graphs and Bayesian networks to diagnose and predict faults in those systems. This paper reviews these graphical model based techniques related to fault diagnosis and prognosis and give suggestions for future research directions identifying research gaps in the field.

KEYWORDS: model-based systems, fault diagnosis, fault prognosis, automata, Petri nets, bond graphs, Bayesian networks.

1 INTRODUCTION

When engineering systems are designed sensors are added for control and feedback purposes, but when a fault occurs or when there is an impending fault in a system, this set of sensors may not be adequate to diagnose it or predict it before it takes place. Examples of this kind of situations would be mechatronic failures of aircrafts, vehicles, power plants, rapid rail transport systems and other safety critical reactive systems.

If the system behaves outside the specified behaviour for it, then we say there is a fault in the system. Failure of a bolt is a permanent fault while a loose wire connection is a temporary fault [1]. These faults are also called parametric faults because they change the system parameters like voltages, speeds etc. When this change is rapid compared to the system sampling time we call it an abrupt fault and an incipient fault, if it is a small drift in system parameters over a longer period.

In fault diagnosis, there are three operations. First is to detect the occurrence, then isolate it to know what and where it has happened, and finally to accommodate it by shutting down the system and replacing the faulty component or reconfiguring the system. In fault prognosis, we observe the system behaviour and if it runs to an unaccepted behaviour alarms are activated [1].

When we analyse the types of solutions provided by the researchers for this problem in model based systems, we can group these into automata related solutions, Petri nets based solutions, bond graph based solutions and Bayesian networks based solutions. All these solutions were used to find solutions in discrete event systems, continuous variable systems and hybrid systems (which is a combination of both types).

Some researchers may also be interested in state space based fault diagnosis techniques which mainly consider continuous variable behaviour of signals from/to sensors and actuators. Model based systems of this type have been reviewed in publications [2], [3], [4], [5] and interested readers may refer to them for more details. This paper covers graphical model-based systems.

2 MOTIVATION

Model based diagnosis/prognosis systems are popular among researchers because these systems perceive the behaviour of the plant through sensors and analyse it online or offline in relation to a formal model of the plant to provide solutions for diagnosis and prognosis issues. Most importantly the model should represent the true behaviour of the plant. Then the decisions will also be realistic.

The model based systems we have chosen are applicable in situations where the plant model, supervisory controller and fault diagnosis/prognosis unit can be modelled separately with the aim of applying it for fault diagnosis/prognosis problems in reconfigurable and evolving safety critical reactive systems.

The authors were unable to find a comprehensive analysis of model based fault diagnosis and prognosis systems applicable to this kind of systems. The aim of this paper is to fill this gap.

3 FAULT DIAGNOSIS APPROACHES

3.1 Automata Based Solutions

1) Approach

An Automaton is a directed graph where nodes represent states and edges represent events. There is a definite transition function which evolves the model from one state to another on input events which takes place in the system (plant and its environment). In literature, there are many types of automata (occasionally the only difference being in the name used for basically the same state transition structure) used to represent system behaviour: Finite Deterministic Automata [6], [7], [8], Finite State Machines (FSMs) [9], [10], [11], [12], [13], [14], Mealy Automata [15], Moore Automata [1], [16], Finite Nondeterministic Automata [17], and Labelled Transition Systems [18], [19], [20]. Generally, in these systems there is a system model based on automata and another automaton for fault diagnosis, which is called the ‘fault diagnoser’ or simply ‘diagnoser’.

Compared to the centralized architecture for systems, distributed and decentralized systems have the ability to being progressively built up by adding module by module to the system with little or no disturbance to the other companion modules. This facilitates easy control and maintenance of larger systems with several local modules. In [15], [21], [22] and [23] researchers investigate the concept of co-diagnosability. Conceptually, it discusses how the system level diagnosability decisions can be made without missing any faults and at the same time without generating false alarms when several local diagnoses are in operation.

In some systems a fault in one unit can have severe effects on dependant (causally downstream) components of the system. For instance, in an aircraft if the landing gear is faulty, even if all other parts are working in normal condition, it could be difficult to control landing properly, which can severely damage even the normally operating parts when landing. Hence, in this kind of situations it is necessary to detect faults before the system executes some more events which can run it to a hazardous state uncontrollably. Similarly there can be situations where a simple fault may result in a very dangerous explosion or destruction. As a solution to this type of faults the concept of safe diagnosability is proposed in [24] and [25]. Technique of safe diagnosability assures the detection of the fault before the system runs into a hazardous state.

The addition of time to the discrete model of Automata can widen their application domain for diagnosability. Timed Automata can be constructed by replacing transitions which fire instantaneously, with transitions which take some time for firing [26], [27] and [28]. This opens up the scope of modelling to continuous variables and thereby hybrid systems using Automata.

2) Applications

To verify their theoretical development researchers have applied automata based techniques to simple systems containing few active components with simple dynamics. For instance, in [10], [11] [29], [30] and [31] application was a HVAC system containing a pump, valve and a controller. In [9] applications are the same HVAC system and a nitric acid cooling system which contains a temperature sensor, a temperature controller, a pump, a control valve, cooling controller valve and a load which can be considered as an extension of the previous HVAC system. In [1] first application is a heating system with a temperature sensor and a controller. The second application is the previous HVAC system discussed in other papers. Most of the other applications are also simple models like these. These systems are modelled as centralized systems, decentralized systems, distributed systems or hierarchical systems. Finally, diagnoser construction procedure and diagnosability conditions are discussed in each case.

Safe diagnosability is also explained with a system containing a valve, pump and a controller [24], [25]. Timed Automata were applied to simple hypothetical systems in [26], [27], [28]. Applications of stochastic systems are discussed in [32], [33] and [34].

Selecting an application to demonstrate a theoretical concept has to satisfy two conditions. First, it should be simple enough not to complicate the illustration because of the complexity of the system model. On the other end, the model should be complicated enough to demonstrate the complex developments which derive from the particular theory.

3) Issues

In [10], [11] [29], [30] and [31] the main issue is that the system and the diagnoser have to be initialized together. The problem here is the need to restart the whole system after each diagnosis, which may not be practicable in many applications; for instance, the discovery of a faulty landing gear in mid-flight. The method in [1] overcomes this problem but applications are similarly simplistic in nature. Also, these systems are only focussed on fault diagnosis. Therefore, prognosis features need to be added for a complete solution. They consider only discrete variables of the system. Hence, there is a need to extend these models for continuous variable and hybrid systems. Another unanswered question is, if the system is discovered not to be diagnosable, then how that system could be converted to a diagnosable system. This is another area to which these systems can be extended. Similarly, if the system is more diagnosable than the required level (with redundant levels of diagnosis which come at a cost), how can that be identified and the number of observable events reduced resulting in reducing the total plant cost? Issue of optimal observability for diagnosis is addressed in [19] and [35]. Commonly in automata based development, researchers take action to model distributed and decentralized systems as centralized models and use them to construct diagnosers, thus sacrificing dearly on scalability of their methods. This again requires rethinking.

Co-diagnosability concept is interesting, but proper applications are difficult to find in the literature for real-time physical systems. Development of useful concepts for diagnosability of systems is necessary, at the same time these algorithms should work within the millisecond range in which most of the systems work.

Safe diagnosability methods can be applied after the occurrence of a faulty event in a system if there are at least few observable events before the set of hazardous string of events occur. Therefore, similar to diagnosability, safe diagnosability also should be analysed in the design stage of the system, adding necessary facilities like sensors that are necessary to perceive observable events. As indicated earlier, the real problems will arise when attempting to apply the concept to a real-scale physical system. Also, it is interesting to analyse whether safe diagnosability is only suitable for a newly designed system or if there are possibilities to apply it to an existing system. This is an open question.

Timed Automata can be applied to continuous systems with all transitions converted to timed-transitions or to hybrid systems by converting only a set of transitions to timed transitions. However, when compared with other modelling tools available for continuous systems like bond graphs the ability to model drifts of system parameters etc. is not so powerful or straight forward when using Timed Automata, because of the assumption of constant slopes for parameters.

As a conclusion for Automata based systems we can state that the development of Automata based techniques in discrete event system diagnosis is at a higher level compared with its development in the continuous domain.

3.2 Petri Net Based Solutions

1) Approach

Petri nets were first proposed by C.A. Petri in 1962 in his Doctoral thesis [36]. A Petri net is a bipartite directed graph. There are two types of nodes available, namely places and transitions. Always directed edges connect different types of nodes, either place to a transition or a transition to a place. Places are associated with a kind of marking called tokens. By moving these tokens according to a set of specified rules the system state mobility is obtained [37]. Activating a transition is called firing. To fire a transition all the input places connected to that transition should be enabled by having the required number of tokens necessary to fire that transition. Once the transition is fired a specified number of tokens will be delivered to each of the output places of that transition, and also a specified number of tokens removed from each of the input places. At a snapshot of time the number of token distribution in all the places of the net is called its marking and this completely describes the state of the system being modelled.

Petri nets have the ability to model synchronization, sequential behaviour, conflict and concurrency [37]. Therefore, it is used to model, centralized [38], [39], [40], [41], [42] decentralized, distributed [43], [44], [45] and hierarchical systems within the framework of failure/fault diagnosis.

Another advantage of using a Petri net to model a system is that the size (number of states and events) of the net is much smaller compared to an Automaton. Therefore, a Petri net always takes less space and thereby less memory and (possibly) less processing time than for an automata-based model. In addition, concepts like conflicts, synchronisation, parallelism can be easily modelled with Petri nets which need more attention when design using Automata. As a result, Petri nets have become a more powerful and popular tool for modelling complex systems. Construction of decentralized and distributed systems [46], [47] also has eventually become an easy task for Petri nets.

Even though Petri nets were initially proposed to model discrete behaviour of systems, later, researchers have extended them to model time, converting the transition to a timed transition which takes some time to fire the transition (called as Timed Petri Nets) [48]. This provided them to extend it to the continuous domain [49] and to develop hybrid models. Further, it was developed into a type of Petri nets called Coloured Petri nets [50], [51] which is a compressed representation of ordinary Petri nets, giving the possibility of modelling a system of virtually any size using very small nets, through the introduction of more and more complex functions on their transitions. However, this added expressive power has not been used very much in the domain of fault diagnosis. To analytically represent uncertainty in fault diagnosis knowledge fuzzy Petri nets were used in [52], [53], [54], [55] and [56].

As the marking of a Petri net gives the state of the system, it is possible to treat the marking graph of the Petri net as an Automaton, thereby facilitating the application of all the theories developed for Automata based models on Petri net models. In [57] and [58] Petri nets are implemented as supervisory controllers on PLCs. Therefore, using the same guidelines it is possible to implement fault diagnosis systems also using PLCs. Implementation of fault diagnosers on FPGA or parallel processor architectures will not be difficult too.

2) Applications

The applications of Petri nets are much wider when compared with Automata. These include manufacturing systems [45], [59], [60] heat exchangers [61] and some hypothetical systems [62], [63], [64], [65]. The reason for this is the power of it to model complex systems.

Application of stochastic Petri nets is discussed in [43]. In decentralized and distributed systems, communication events can be easily modelled with transitions of Petri nets. There is a wide variety of applications of Petri nets in manufacturing outside fault diagnosis context also. Supervisory control and deadlock avoidance [66], [67], [68], [69] have been major applications of Petri nets in manufacturing plants.

3) Issues

The main challenge of using Petri nets would be to represent the system accurately using Petri nets. These include selecting places and transitions, allocating a number of tokens for places, allocating arc weights if necessary and times for transitions if time is considered. The reason is any error in these allocations can take the model away from the actual plant considered.

Another issue is if we need to model the system as a distributed system, sometimes these modules may not be directly identifiable or separable from other units in the system. Therefore, we have to consider methods like those proposed in [44], [58], [70] and divide the system into manageable local modules.

Unlike in other approaches, we can see the knowledge management technique fuzzy logic also integrated with Petri nets. This shows us, compared to other systems, Petri net based approaches are well developed in the area of fault diagnosis and prognosis integrating other powerful technologies.

3.3 Bond Graph Based Solutions

1) Approach

A bond graph is a labelled directed graph. Edges are of two types, namely bonds and signals. Nodes are multiport which means there is a possibility to connect many edges to the port. Number of ports on a node depends on the number of edges connected to it. A bond is represented by a half arrow and a signal is represented by a full arrow. A detailed procedure of constructing bond graphs can be found in references [71], [72], [73] and [74].

Bond graphs show the relationships of effort and flow variables of connected nodes. Initially, bond graphs were constructed to model continuous systems. As it can model, resistive, capacitive, inductive and inertia loads together with transformation units like transformer and gyrator units it has become a powerful tool among engineers and scientists for modelling hydraulic, electric, electronic, mechanical or any other physical system. Hence, today as the technology is heading towards a mechatronic world, bond graph has become a powerful tool which can satisfy these modelling requirements. Bond graphs can be used to derive system equations from the model.

2) Applications

Ability of bond graphs to model various kinds of systems has become a factor to apply them, especially in the area of Control Engineering [75], [76], [77], [78], [79]. In these references, bond graphs were used to model flexible robotic manipulators, 4W-vehicle suspension systems, high speed railway traction devices, solar heated houses and two stage pressure relief valves. This range shows the capacity of bond graphs to model physical systems with a huge variety.

Bond graphs are applied for fault diagnosis of continuous systems in [80], [81], [82], [83] and [84]. Then researchers understood if they need to get the maximum contribution from bond graphs for their models they need to merge the ability to model discrete variables also in their models. This gives rise to hybrid bond graph technology. One of the attempts to model this discrete behaviour is by introducing a switch. This switch will switch on and off branches of the bond graph according to the state of a discrete variable. This technique was illustrated in [85], [86], [87], [88], [89]. This switching behaviour is further improved in [90], [91] including causality. Hybrid bond graphs were applied for robust systems in [92].

In the context of fault diagnosis, development of a Temporal Causal Graph (TCG) facilitates driving a fault diagnoser from the bond graph model. This technique was applied in [93], [94], [95], [96] and [97]. The fault diagnoser is implemented as a Bayesian network. By assigning suitable conditional probability values to the network it can be used as a fault diagnoser for the bond graph model [98], [99], [100], [101].

Causal relationships in TCG can be used to determine the minimal overdetermined subset of equations in a bond graph. These equations can be then used to identify Possible Conflicts (PCs) in the bond graph and the related sections of the bond graph. This was used for fault diagnosis using bond graphs in [102], [103], [104], [105], [106]. This concept is also applicable in hybrid systems. Hence, the concept of possible conflicts strengthens the fault diagnosis capacity of bond graph techniques.

By integrating Hidden Markov models with Bayesian networks a Dynamic Bayesian Network (DBN) can be constructed. This approach was applied in dynamic systems and/or hybrid systems for fault diagnosis [107], [108], [109], [110].

3) Issues

As discussed earlier bond graph is one of the best modelling techniques used by researchers to model continuous systems. But as we saw earlier discrete behaviour is integrated in to this model as a switch which enables and disables branches of the graph. When compared with the capacity to model and perform fault diagnosis in a discrete system using automata or Petri nets, the ability of bond graphs can be considered as lagging far behind. Therefore, it is necessary to have an integrated method for bond graphs to handle discrete behaviour like in other tools.

4 FAULT PROGNOSIS APPROACHES

4.1 Automata Based Solutions

1) Approach

Using Hybrid Automata for fault prognosis is common. The reason is the capacity to handle both discrete events and continuous variables [111]. In [112] degradation of the system model is represented by a Weibull probability distribution and used for fault prognosis.

Another approach to model for prognosis is to model the system using Timed Automata [113]. The ability of modelling time in this type of systems has been used successfully for fault prediction. In [8] and [114] an automaton has been modified to generate a fault prognoser which can perform robust fault prognosis.

A Finite Nondeterministic Automaton was employed for fault prognosis of *distributed* systems in [115] and [116]. This is a more complicated model because for one input event there can be several output states. When modelling real world systems with less number of approximations, the model will become more complicated and as a result processing issues and complexity of the model can create difficulties in implementation.

2) Applications

Most of the work done in this area used hypothetical systems to illustrate techniques developed by them. This may be because of the difficulty of finding a simple application which fits exactly the situation.

3) Issues

While designing the system as a hybrid system, an ageing technique is applied to model the time evolution of the system in reference [112]. In general, hybrid systems have separate fault diagnosis and fault prognosis units. However, since both of these modules share the same sensory inputs, the modelling efficiency may be increased by integrating them. Then some faults already diagnosed can be inputs to fault prognosis and vice versa. The reason is, if it is a dynamic system, the processing, diagnosis and prognosis should be sufficiently fast not to miss any events in the system.

As stated above one issue with most of the solutions is the extra-simplistic nature of examples they have chosen. And in methods where the real time models which use Timed Automata are converted to untimed models to analyse failures and do prediction [113] there is a possibility of losing information related to real time operation. To validate the relevance of these results, the behavioural equivalence of the two types of models must either be proven theoretically or demonstrated by applying the results back into real time models.

Most of the models consider the sensors and transducers used are working perfectly all the time. But in the real situation they also deteriorate. Hence, their fault diagnosis and prognosis models should be extended to an architecture which can handle such deterioration/failures or the model should be robust enough to handle sensor failures. Handling sensor failures will also be a good area of research in the same line.

4.2 Petri Net Based Solutions

1) Approach

When designing the system, there is a possibility of inserting sensors to detect some of the events and markings of the Petri net. This kind of a Petri net is called a partially observed Petri net. Later, the model can be used to detect failures and to forecast future failures. This kind of approaches are reported in [117], [118], [119], [120] and [121].

2) Applications

In reference [111], the application was a single water tank system. In [118] and [121] a conveyor network was used as the example system and partially observed Petri nets were used as the modelling tool.

3) Issues

If more accurate prediction is needed, the number of sensors being employed to detect states and important observations need to be increased. There are no methods proposed to compute the optimal number of sensors required in this architecture. Main advantage in these methods is that they do not require to detect the system initialization to run the algorithm, but need only the present condition of part of the system one is interested in. Therefore, one can use this method locally to a specific part of the system which one is more interested in, or somehow more critical. This can save on cost of sensors.

4.3 Bond Graph Based Solutions

1) Approach

Unlike in the general Bayesian networks, dynamic Bayesian networks model the evolution of the system with time. This technology allowed researchers to use bond graph generated Bayesian networks for fault prognosis tasks.

In prognosis using dynamic Bayesian networks, probabilistic reasoning is used to estimate the possible future states of the system. Using these states Remaining Useful Life (RUL) is estimated in days, hours, minutes or cycles, depending on the type of system under consideration. If the last executed state of the system is known, the RUL of the component being considered can be estimated.

2) Applications

Reference [122] uses a dynamic seal in a hydraulic actuator for illustrations. The fault prognosis of a high speed railway traction device was done using bond graphs based Bayesian network in [77]. In [123] the methodology for fault prognosis was extended using particle swarm optimization for multiple failure prognosis. This time the application was a hybrid system in electronics. When compared to other two methods, applications of bond graph based techniques for fault prognosis are rare.

3) Issues

Many researchers use Dynamic Bayesian Networks together with Bond graphs for fault detection, diagnosis and prognosis. Even Hybrid-Bond graphs which can model both continuous parameters and discrete events using the method of possible conflicts can be applied in many situations. Good and fast algorithms have been proposed for fault prognosis using Dynamic Bayesian Networks. Bayesian estimation and EM algorithm are adopted to generate conditional probability distributions required for Bayesian networks.

Learning in Bayesian networks and fault diagnosis and prognosis need a high degree of computational power. Therefore, applying computational complexity reduction methods such as particle filtering and similar technologies will be useful, but maintaining the fault detection and prediction power at the same time will be a challenge. Also, applying these technologies for complex real systems will be a challenge not only because of the expected computational power, but also because of the other issues like signal conditioning, noise filtering and related issues.

5. CONCLUSION

This paper summarizes graphical model based systems widely used in the context of fault diagnosis and prognosis. We only looked for solutions with discrete events and timed events because comprehensive reviews of literature related to state space models of continuous variable systems are already available in [2], [3], [4], [5]. In summary,

- Automata based solutions for discrete event systems related fault diagnosis and prognosis is developed to a high degree, but the situations where these solutions have been applied to complex real world systems are rare.
- In automata based methods, continuous variable parametric systems were approximated with timed automata. Events in here only consider the start and the finish of firing the event. The dynamics of the variables in between are neglected. Variables are considered to have fixed slopes. But in fault diagnosis and prognosis of continuous variable parameters the behaviour of the system in between also can be important.
- Solutions for the same using Petri net based approaches are successful, but again the transitions in Petri nets for continuous variable systems are similar to event firings of Timed Automata.
- Mathematical models developed mainly for fault diagnosis of continuous variable systems only.
- Bond graphs which are generally used with continuous variable systems have been extended to include discrete event behaviour using techniques of possible conflicts and switching systems. Fault diagnosis and prognosis are done using Temporal Causal Graphs, Bayesian Networks and Dynamic Bayesian Networks.
- Strengths and weaknesses can be identified in each method proposed. Generally, when the method behaves more promisingly with discrete event systems the continuous variable behaviour may not be properly represented and vice versa. This is because the strengths of modelling techniques and their capacity to represent the actual system behaviour are limited.
- Finally, the objective of many research efforts has been to develop an effective framework for fault diagnosis and prognosis of the integrated type of systems containing discrete events and continuous parametric variables, but to get an exact representation, models that perform well with discrete event systems need to be integrated with models which can accurately represent continuous variables.

Table 1 Summary of Literature

Reference	Approach	Fault: Diagnosis	Fault: Prognosis	Type of System: Central.	Type of System: Decentralized	Type of System: Distributed	System
[1], [9], [10], [11], [12], [16], [18], [19], [29], [30], [31], [32], [34], [35], [65]	Automata	✓		✓			Discrete
[8], [15], [17], [21], [23], [33], [35]	Automata	✓			✓		Discrete
[6], [7], [13], [20], [22], [29], [32]	Automata	✓				✓	Discrete
[24], [25]	Automata		✓	✓			Discrete
[14]	Automata		✓			✓	Discrete
[26], [28]	Automata	✓		✓			Continuous
[27]	Automata and Bond Graph	✓		✓			Continuous
[36], [37], [38], [39], [40], [41], [42], [47], [59], [62], [64], [65], [119]	Petri net	✓		✓			Discrete
[36], [37], [44], [45], [63]	Petri net	✓			✓		Discrete
[36], [37], [43], [44], [46], [47], [61], [70]	Petri net	✓				✓	Discrete
[48], [49]	Petri net	✓		✓			Continuous
[52], [53], [54], [55], [56]	Fuzzy Petri nets	✓		✓	✓	✓	Discrete
[76], [77], [78], [79], [80], [81], [82], [83], [84], [93]	Bond Graph	✓		✓			Continuous
[77]	Bayesian Network	✓		✓			Continuous
[85], [86], [87], [88], [89], [92], [94], [96], [97], [100], [101], [102], [103], [104], [105], [106], [108], [109]	Bond Graph	✓		✓			Hybrid
[90], [91]	Automata	✓		✓			Hybrid
[95], [98], [99], [100], [107], [108], [109], [110]	Bayesian Network Approach	✓		✓			Continuous and Hybrid
[111], [113]	Automata		✓	✓			Hybrid
[112]	Automata	✓	✓	✓			Hybrid

[115]	Automata		✓			✓	Discrete
[114]	Automata		✓	✓			Discrete
[116]	Automata		✓		✓		Discrete
[117]	Petri Net		✓	✓			Discrete
[118], [120]	Petri Net	✓	✓	✓			Discrete
[121]	Petri Net	✓	✓	✓			Continuous
[122]	Bayesian Network Approach	✓	✓	✓			Hybrid
[123]	Bond Graph	✓	✓	✓			Hybrid

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