Chapter 10
Overall Conclusion and Discussion

Since bond graphs were devised by Professor Paynter [1] more than five decades ago, they have been mostly used for the development of continuous time models of multidisciplinary engineering systems in order to study the dynamic behaviour of a system. In addition, intensive research has been carried out and various approaches have been proposed how to account for the abstraction of discontinuities in a bond graph framework and how to extend bond graph methodology to systems suitably described by a hybrid model. More recently, bond graphs have also been used for model-based FDI of systems described by a continuous time model. So far, none of the reported approaches has attained common usage.

This book shows that standard bond graph modelling can also support model-based

- fault detection and isolation,
- system mode identification, and
- failure prognosis

for systems described by a hybrid model. Devices with fast state transitions such as diodes, transistors, hydraulic valves, are modelled as non-ideal switches. Following a proposal of Ducreux et al. [2], they are represented in bond graphs by an MTF controlled by a modulus $m(t) \in \{0, 1\} \; \forall \, t \geq 0$ and an ON-resistor in fixed, mode-independent conductance causality. Causal conflicts that may occur at junctions are resolved by attaching an auxiliary element. Equations deduced from a bond graph are formulated such that the parameter of the auxiliary elements can be set to zero. Recently, a different approach to FDI for hybrid systems using controlled junctions has been proposed by Wang et al. [3].

If the abstraction of instantaneous state transitions is adopted then a switching device such as a mechanical clutch causes a change in the model structure. As a result, storage elements may become dependent. That is, the number of state variables become mode-dependent. One approach to this problem is to detect discrete system mode changes while simulating the dynamic system behaviour, to use a different mathematical model for the dynamics in each mode and to re-initialise numerical integration at the event of a discrete mode change when necessary. In order to keep

W. Borutzky, *Bond Graph Model-based Fault Diagnosis of Hybrid Systems*,
DOI 10.1007/978-3-319-11860-4_10

integral causality at storage ports independent of the system mode, residual sinks may be used that are switched on and off. When two storage storage elements become dependent due to a switch state change they supply an output that forces the two storage elements in integral causality to produce a joint output.

With regard to a simulation of the dynamic behaviour of a system represented by a hybrid model, this approach offers the following advantages.

- A BG with static causalities can be developed that holds for all system modes, i.e. causalities do not change with the commutations of switches.
- The standard SCAP can be applied without any modifications.
- A single set of mode-dependent equations of motions can be derived from a BG.
- Existing software could be used for the generation of equations.

Equations can be formulated so that parameters of auxiliary elements can be set to zero. Also, the ON-resistance of switches can be set to zero turning them into ideal switches so that small time constants and thus a set of stiff model equations can be avoided. In the case residual sinks are used, which is similar to the use of Lagrange multipliers, the resulting mathematical model is a DAE system of index 2.

As to FDI, mode-dependent ARRs can be deduced from a DBG with storage elements in derivative causality and sensors in inverted causality. Their structure is captured in an all-mode FSM. An evaluation of ARRs yields residuals that are used as fault indicators. In general, ARRs relate time derivatives of known variables. The necessary differentiation is carried out in discrete time.

Alternatively, for off-line simulation, a behavioural model of a real system subject to faults and a reference model with nominal parameters can be coupled by residual sinks. Their outputs being ARRs residuals force the nominal model to adapt to the behaviour of the faulty system model. In this approach, the two coupled bond graphs are in integral causality. Advantage of this approach are that

- all kinds of faults can be deliberately introduced into the behavioural model of the real process without any risk,
- ARR residuals can be numerically computed as unknowns of a mode-dependent DAE system. There is no need for ARRs in closed symbolic form.

For online simulation, the outputs of the behavioural model are to be replaced by measured outputs from the real system. As measurements carry noise they must be appropriately filtered.

ARR residuals serving as fault indicators should be distinguishably sensitive to true faults but little sensitive to noise and parameter faults in order to avoid false alarms on the one hand side and to make sure that fault detection does not miss any faults. Therefore, appropriate thresholds for ARR residuals are to be set. As the dynamic behaviour of hybrid systems can be quite different in different modes, predefined bounds of constant value may not be suitable. In this book, the incremental bond graph approach [4] has been briefly recalled and applied to hybrid system models to deduce adaptive mode-dependent ARR residual thresholds that account for parameter uncertainties.

If component parameters in a system mode share a fault signature in the FSM then a fault can be detected but not isolated by simple inspection of the FSM. In case online fault detection provides a coherence vector that matches with more than one row in the FSM in a system mode, the result is a set of potential fault candidates. One way to identify multiple faults is to perform parameter estimation by Gauss-Newton least squares output error minimisation. Bond graph modelling can support this approach to multiple fault isolation by providing ARRs. Their residuals are used in the functional to be minimised. This has been discussed in Chap. 6.

As ARRs derived from a hybrid model are mode dependent, it is important for an online FDI to know the current mode in order to use the correct values of the discrete states in the ARRs so that ARR residuals can serve as indicators of fault in the current system mode. It turns out that an evaluation of all ARRs or a subset of ARRs in case the previous mode is known can be used to identify the current system mode. The task can be performed in parallel in order to minimise the response time.

For illustration, in Chap. 8, the proposed bond graph model-based approach to FDI for hybrid systems has been applied to small often used power electronic systems. As those systems contain semiconductor power switches that are usually commutated at high frequency and are subject to typically open circuit and short circuit faults, they are well suited for FDI case studies. Furthermore, power electronic systems are part of mechatronic systems such as hybrid vehicles, or wind turbines which suggests to apply bond graph modelling. As failures in a power electronic subsystem affect the overall dynamic behaviour of a system and its performance it is important to apply FDI methods in order to avoid malfunctions or damages in the load of power electronic system. Therefore, it is not surprising that FDI in power electronic systems, especially in motor drives, has been a subject of many publications. The majority of them, however, does not use bond graph modelling. Clearly, the bond graph model-based approach to FDI proposed in this book is not confined to power electronic systems. The case study of the switched three phase power inverter, for instance, could be extended in further research. The RL-load could be replaced by an elaborated model of an induction motor and its mechanical load.

Finally, in comparison to fault diagnosis which has been a subject of a lot of research and has become established in industry, failure prognosis is yet a relatively young field. Fault detection, isolation and fault accommodation react to faults that had happened, while failure prognosis aims at assessing the current health of a system and to predict the remaining useful life or time to failure. This is of importance for maintenance in order to reduce costs while increasing reliability, availability and security of a system, of machinery or of equipment. Chapter 9 shows that ARRs derived from a bond graph can also support model-based failure prognosis for hybrid systems. If fault diagnosis has detected and isolated an incipient parametric fault then the time evolution of an ARR residual over a certain window and known inputs into the ARR define a degradation profile of the faulty parameter that is to be matched with a mathematical degradation model from a set of potentially appropriate models. The unknown parameters in this model can be determined by nonlinear least square parameter estimation. Once the parameters of the degradation model are available, the RUL of the faulty component can be determined by computing the time from the starting point of the incipient fault until the trend of the parameter intersects with a suitably defined failure alarm threshold. Chapter 9 considers a simple network with one switch for illustration. It is expected that bond graph model-based failure prognosis will be subject for further research.

The focus of this book has been on the presentation of a bond graph model-based approach to FDI and failure prognosis for hybrid systems. It turns out that ARRs derived from a bond graph play a key role in all tasks that have been considered, in FDI, in system mode identification and in failure prognosis. Simulation results have been obtained by using the dassl solver as part of the open source software Scilab [5].

As hybrid models include discrete state events, i.e. instantaneous state discontinuities, numerical multistep integration methods seem not to be particularly suited for their solution. The time instant of such discrete events must be located by constantly evaluating zero-crossing functions and by adjusting the integration step size. Once the time instant of a discrete event is located, numerical integration must be re-initialised. The necessary computational time may be of relevance in simulations of fault scenarios. Diagnostic models for generating ARRs use derivative causality at storage ports. The necessary differentiation with respect to time is usually performed in discrete time. Discontinuities in the inputs of the model, however, result in pulses.

DEVS simulation using state quantisation instead of time discretisation as outlined in Chap. 1 seems to be better suited for handling instantaneous state discontinuities. In comparison to the evolution of sophisticated numerical integration methods for DAE systems, the use of quantised state integration and the application of the DEVS methodology to hybrid system models is a rather young approach that still needs some problems to be addressed. However, the use of QSS and DEVS simulation for FDI in hybrid systems may be another subject of further research.

A topic that hasn't been considered in this book but is closely related to fault diagnosis is fault tolerant control (FTC) [6]. A 2008 bibliographical review on reconfigurable fault-tolerant control systems may be found in [7]. The aim is to react to a fault that has been detected and isolated so that the system can continue its operation in the presence of a component fault and to ensure safety at the same time. Fault tolerant strategies are categorised into two classes depending on whether they use a passive or an active approach [8]. Passive FTC relies on a robust controller of fixed structure that enables to cope with a set of faults taken into account at the stage of system design. A bond graph approach to passive fault-tolerant control of systems described by continuous-time model has been presented in [9]. Active FTC (AFTC) is a challenging task because the parameters of a control algorithm or even the algorithm is to be changed online by a supervision system. The integration of FDI and reconfigurable control for active fault-tolerant control systems has been addressed in [10]. Figure 10.1 displays the general scheme of active FTC.

In any case, FDI is a prerequisite also for this task and bond graph based ARR residual generation can provide the information needed by fault diagnosis. Chapter 11 of reference [11] addresses fault tolerant control of systems represented by continuous time model and related issues such as system inversion. In [12], a bond graph approach to diagnosis and FTC has been recently presented and applied to an intelligent autonomous vehicle. FTC of hybrid systems has been considered for instance

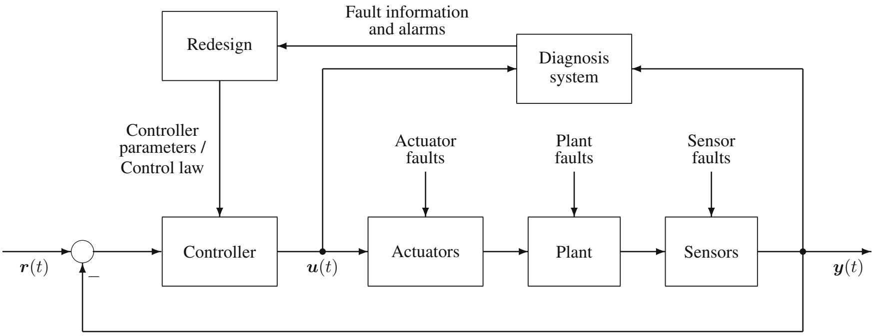

Fig. 10.1 General scheme of active FTC

in [13] without using bond graphs. A fault tolerant control approach for switched LTI systems has been proposed in [14] that uses bond graphs for mode identification and observer-based reliable state feedback control focusing on the time delay between FDI and fault accommodation during which still the original control law is applied to the faulty system.

References

1. Paynter, H. M. (1961). *Analysis and Design of Engineering Systems*. Cambridge: M.I.T. Press.
2. Ducreux, J. P., Dauphin-Tanguy, G., Rombaut, C. (1993). Bond graph modelling of commutation phenomena in power electronic circuits. In: J. J. Granda & F. E. Cellier (Eds.), *International Conference on Bond Graph Modeling, ICBGM'93, Proceedings of the 1993 Western Simulation Multiconference*. Simulation Series, 25(2) (pp. 132–136). San Diego: SCS Publishing. ISBN: 1-56555-019-6.
3. Wang, D., Yu, M., Low, C., & Arogeti, S. (2013). *Model-based health monitoring of hybrid systems*. New York: Springer.
4. Borutzky, W. (Ed.). (2011). *Bond graph modelling of engineering systems - theory, applications and software support*. New York: Springer.
5. Scilab Enterprises. 78000 Versailles, France. Available from: http://www.scilab.org/.
6. Blanke, M., Frei, C., Kraus, F., Patton, R., Staroswiecki, M. (2000). What is fault-tolerant control? Aalborg University, Department of Control Engineering. Available from: http://www.iau.dtu.dk/secretary/pdf/safeprocess_02h.pdf.
7. Zhang, Y., & Jiang, J. (2008). Bibliographical review on reconfigurable fault-tolerant control systems. *Annual Reviews in Control*, *32*, 229–252.
8. Patton, R. J. (1997). Fault-tolerant control systems: the 1997 situation. In *Proceedings of 3rd IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes* (pp. 1033–1055). Available from: http://hull.ac.uk/control/downloads/safepr.pdf.
9. Nacusse, M., Junco, S. J. (2011). Passive fault tolerant control: a bond graph approach. In A. Bruzzone, G. Dauphin-Tanguy, S. Junco, M. A. Piera (Eds.), *Proceedings of 5th International Conference on Integrated Modelling and Analysis in Applied Control and Automation* (IMAACA 2011) (pp. 75–82). Rome, Italy: Diptem Universit Di Genova.
10. Zhang, Y., Jiang, J. (2006). Issues on integration of fault diagnosis and reconfigurable control in active fault-tolerant control. In *Fault Detection, Supervision and Safety of Technical Processes* (pp. 1437–1448). Vol 6, Part 1. P.R. China: Tsinghua University.

11. Samantaray, A. K., & Ould Bouamama, B. (2008). *Model-based process supervision - A bond graph approach.*, Advances in Industrial Control London: Springer.
12. Loureiro, R. (2012). Bond graph model based on structural diagnosability and recoverability analysis: Application to intelligent autonomous vehicles [PhD thesis]. L' Université Lille 1.
13. Ocampo-Martinez, C., & Puig, V. (2009). Faul-tolerant model predictive control within the hybrid systems framework: application to sewer networks. *International Journal of Adaptive Control and Signal Processing.*, *23*(8), 757–787.
14. Hao, Y. A. N. G., Ze-Hui, M. A. O., & JIANG, Bin. (2006). Model-based fault tolerant control for hybrid dynamic systems with sensor faults. *Acta Automatica Sinica.*, *32*(5), 680–685.