Automatic Construction of Processes from a Bond Graph Representation

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Abstract

The aim of this paper is to propose an automatic method to construct a process model from a bond graph representation. The system is described in a multimodeling approach. In this approach several models represent the functional knowledge: the functional role model and the process model. Functional roles are in correspondance with bond graph elements and it is shown that the causality and the orientation of the energy flow have to be taken into account in order to build the processes cofunctions. An algorithm is given which constructs these cofunctions from the bond graph representation. This method is applied to construct the processes of a nuclear power plant coolant loop and is illustrated on a simplified part of this system. The methods based on the multimodeling approach for interpreting or for diagnosing systems can usefully rely upon this automatic construction of processes.

Introduction

Model based reasoning is a subfield of AI focusing on device understanding issues. Initially, it was based on the works of de Kleer, Forbus and Kuipers on qualitative reasoning. These approches were limited to use structural and behavioral knowledge.

In order to provide an additional information for understanding and reasoning about the structure and the behavior of a system, several research was focused on functional modeling and functional reasoning. Most of it consider the function as what is expected and the behavior as how this expected result is attained. (Sticklen & Chandrasekaran 1989), (Hawkins, Sticklen, & Mcdowell 1994) and (Keuneke 1991) represent and explain complex system mechanisms by combining the following knowledge: the structure specifies the system components and their relationships, the function specifies the goal of the system or the component activity, and the behavior specifies how the function is accomplished. The behavioral model is represented as a causal sequence of states. (Keuneke 1991) defines an additional distinction of functions. She classifies functions into four types: ToMake, ToMaintain, ToPrevent and ToControl. (Vescovi *et al.* 1993) and (Chandrasekaran 1994) consider another formalism for representing system functions. They describe the functional goal of the system by a boolean combination of Causal Process Descriptions (CPDs). Each CPD is an abstract description of expected behavior in terms of a causal sequence of events. Larsson (Larsson 1996) exploits in his reasoning task a functional and teleological representation called Multilevel Flow Models (MFM). There are three function types considered in MFM: mass and energy flow function (source, transport, barrier, storage, balance and sink), information flow function (observer, decision maker and actor) and organizational functions (network and manager). This approach proposes a graphical language to represent goals, functions and relations. However it doesn't explain how functions can be derived.

(Chittaro *et al.* 1993) propose an other method to specify the functional processes of the system. They consider three possible physical processes: transporting, charging and discharging. Each process is defined by a network of functional roles (generator of effort or flow, reservoir of displacement or impulse and conduit of effort or flow).

Our work focuses on the following two types of knowledge: the bond graph to represent the behavioral model and the processes as described in (Chittaro *et al.* 1993) to represent the functional knowledge. In a previous work (Zouaoui, Thétiot, & Dumas 1997), we presented a method for constructing directly the functional role model from the bond graph. The next step was to use the functional role model to construct the process model according to the definitions in (Chittaro *et al.* 1993). Unfortunately, the direct derivation of process cofunctions from the functional role model allows the construction of a lot of processes and most of them cannot be interpreted. Indeed, each process must correspond to an energy flow but the functional role model does not take into account these flows. Our goal is to construct "real" processes, it means only processes corresponding to an interpretable energy flow.

In section we give an overview of the bond graph theory and in section we recall briefly the definitions of processes in the multimodeling approach. Then in section and , we point out the problem to be tack-

led, namely the use of causality and direction in energy flow when constructing process cofunctions. The section presents a method for constructing automatically process cofunctions and an illustration of this algorithm on the hydraulic part of the Pressurized Water Reactor primary coolant loop is given in section . To conclude, in section , we give some possible applications of this work and some lines of future research to extend it.

The bond graph theory

We use a bond graph representation of a system as the source of the behavioral knowledge. In a bond graph (Rosenberg & Karnopp 1983), the system is decomposed into several basic elements separated and linked by bonds through which energy (power) is transferred. The power flow in every bond is split into the product of an effort and a flow. In mechanics, the effort and the flow correspond to the force and the velocity, in electricity to the voltage and the current and in hydraulics to the pressure and the volume flow rate. The direction of the power flow (positive product of an effort by a flow) is represented by an half arrow. We can define the time integral of an effort (resp. a flow) as the generalized momentum (resp. the generalized displacement). In mechanics, the generalized momentum and the generalized displacement correspond to the momentum and the distance, in electricity to the flux linkage and the charge, in hydraulics to the integral of pressure and the volume. The basic elements of a bond graph are the resistor R (dissipative element), the capacitor C and the inductor I (energy storage elements), the transformer and the gyrator (conservative elements), the effort and flow sources (energy source elements). There are also junction structure elements: 0-junction (parallel) and 1-junction (serial). The 0-junction is a flow balance junction or a common effort junction, it has a single effort on all its bonds and the algebraic sum of flows is null. The 1-junction is an effort balance junction or a common flow junction, it has a single flow on all its bonds and the algebraic sum of efforts is null.

The causality in bond graphs is based on the impossibility to impose or to control both effort and flow simultaneously. The little stroke at the extremity of a bond shows the direction where the effort is applied. Sources have a fixed causality, because they impose effort or flow, depending on their nature. Resistor has no preference. Energy storage elements have preferred causality (integral causality). A capacitor prefers to produce an effort, while an inductor prefers to produce a flow. This property of the bond graph theory gives the possibility of generating a causal graph from a bond graph.

The processes

Each process represents an energy (power) flow between a source of energy and a sink of energy. This flow is running through a succession of components. These components are described in terms of bond graph elements in the bond graph or in terms of functional roles in the functional role model. In (Zouaoui, Thétiot, & Dumas 1997) we showed the correspondance between bond graph elements and functional roles (fig 1). A generator functional role $G_{e,f}$ corresponds to a source bond graph element $S_{e,f}$. A conduit of flow C^f (resp. of effort C^e) dissipating effort (resp. flow) corresponds to a resistor connected to a 1-junction (resp. a 0-junction). A reservoir of displacement R^q (resp. momentum R^p) corresponds to a capacitor (resp. an inductor). A purely conductive conduit CC corresponds to a gyrator or a transformer.

Functional Roles	Bond Graph Elements
G_e	$S_e \longrightarrow 1$ $S_e \longrightarrow 0$
G_f	$S_f \longmapsto 1$ $S_f \longmapsto 0$
C^f	$R \longleftarrow 1$ $R \longleftarrow 1$
C^e	$R \longleftarrow 0$ $R \longleftarrow 0$
R^q	$C \longleftarrow 1$ $C \longleftarrow 1$
	$C \longleftarrow 0$ $C \longleftarrow 0$
R^p	$I \longleftarrow 1$ $I \longleftarrow 1$
	$I \longleftarrow 0$ $I \longleftarrow 0$
CC	$\longrightarrow GY \longmapsto$ $\longmapsto GY \longrightarrow$
	$\longrightarrow TF \longrightarrow$ $\longmapsto TF \longmapsto$

Figure 1: Functional Roles and Bond Graph Elements

A process is described as a four-tuple $<cofunction, precondition, effect, posteffect>$, where:

- *Cofunction* is the ordered list of functional roles necessary to enable the occurrence of the process.
- *Precondition* characterizes the situation which enables the process to occur.
- *Effect and Posteffect* characterize the situation respectively during the occurrence of the process and after the end of the process.

Chittaro and al. proposed some generic process cofunctions ((Chittaro *et al.* 1993)).

- TRANS: transporting. This process represents an energy flow between a source and a sink. It involves a generator, a conduit and a second generator which plays the role of the sink. The cofunction is: $G-C-(G)$. Note that the sink may be implicit.

- CHARG: reservoir charging. This process represents an energy storage in a reservoir. It involves a generator, a conduit and a reservoir. The reservoir plays the role of the sink. The cofunction is: $G - C - R$.
- DCHARG: reservoir discharging. This process represents an energy release out of a reservoir. It involves a reservoir, a conduit and a generator. The generator plays the role of the sink. The cofunction is: $R - C - G$.

Recovering causality

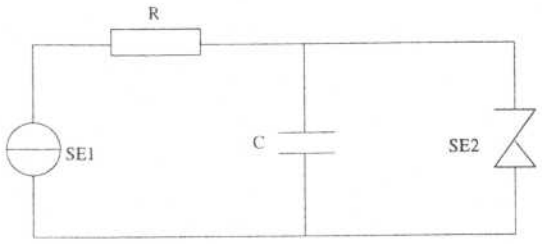

Figure 2: Example

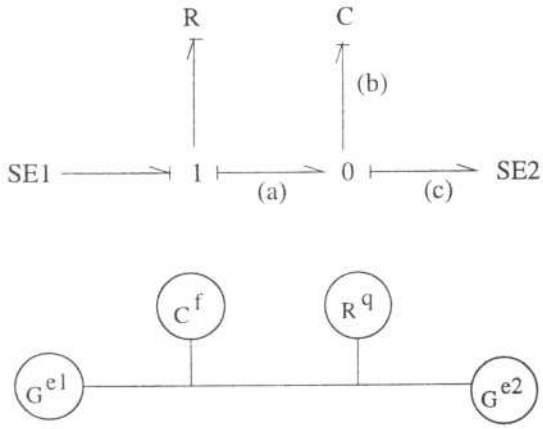

Figure 3: Bond graph of the example

In this section we are going to illustrate the problem happening if we do not take causality into account. The example involves a voltage source, a resistor, a capacitor and a Zener diode (figure 2). In this example the diode voltage V is above the diode threshold V_0 and the diode can accept any value of flow. From this example we construct the bond graph at the top of figure 3 where the Zener diode plays the role of the source $SE2$. According to the correspondance shown in figure 1 the bond graph at the top of figure 3 corresponds to the functional role model at the bottom of figure 3. From the functional role model we can construct two different processes according to Chittaro's definition of process cofunctions (TRANS, CHARG, DCHARG). The first one P_1 would be a charging one and involves G^{e1} - C^f - R^q, the second one P_2 is a transport one and involves G^{e1} - C^f - G^{e2}. The power flow is for the bond (a) $P_a = e * f_a$, for the bond (b) $P_b = e * f_b$, for the bond (c): $P_c = e * f_c$. The power balance on the 0-junction is $P_a - P_b - P_c = 0$. As the effort is the same in the three bonds the power balance becomes a flow balance: $f_a - f_b - f_c = 0$. The flows f_a and f_b are totally independent due to the causality on the 0-junction (cf. strokes on figure 3). f_b is imposed by C in response to $SE2$ and f_a is imposed by R in response to the effort balance between $SE1$ and $SE2$. So a process P_1 representing a power flow between the source $SE1$ and the capacitor C cannot exist because the two flows are independent. Actually, on this example (figure 2), it is impossible to charge the capacitor thanks to the voltage source. For example, given a voltage pulse from V_0 to V imposed by the voltage source, all the current flows through the diode and no current flows through the capacitor. We clearly see this fact on figure 4 showing the three bond graphs constructed when we suppress successively one bond of the 0-junction. The first bond graph corresponds to the process P_1, in this case the 0-junction does not respect the rules for causality assignment. The transporting process P_2 respects these rules and we can construct a process P_3 involving R^q - G^{e2}. It corresponds to a discharging process. This example shows that we must take into account the causality on each crossed junction when constructing a process from a bond graph . A process cofunction cannot be constructed independently of the causality imposed by each bond graph element.

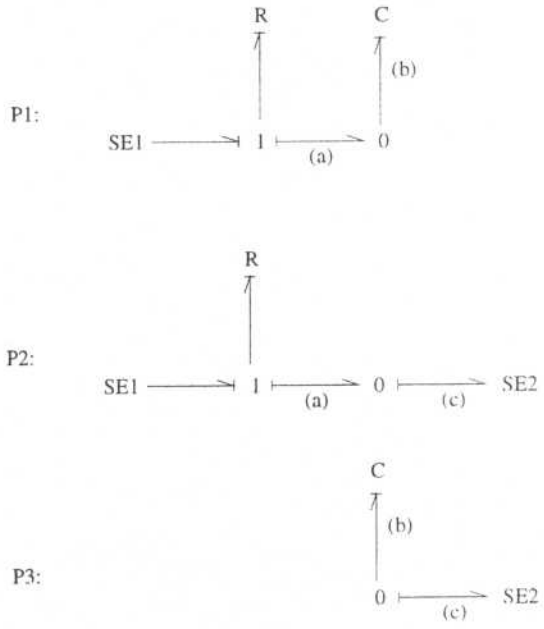

Figure 4: Isolation of processes in the example

Oriented energy flow

In this section we will illustrate the fact that the energy flow orientation must be taken into account in order to construct interpretable process cofunctions. In figure 5

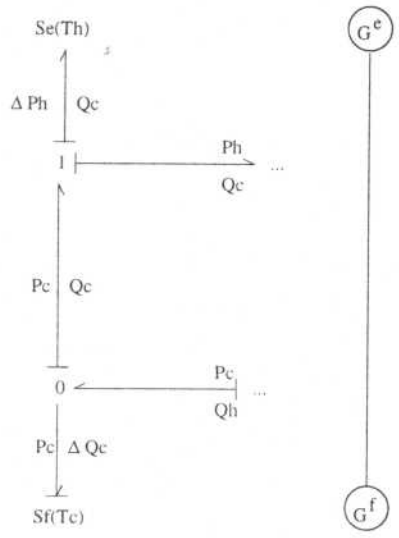

Figure 5: Sub-part of the PWR primary coolant bond graph and corresponding functional role model

we can see a sub-part of the bond graph of the hydraulic part of the PWR primary coolant loop (figure 8). According to this figure we can construct the corresponding functional role model (figure 5). When constructing a process cofunction according to the causality we get the cofunction: $G^f_{T_c} - G^e_{T_h}$. On the bond graph we can see that:

- The power absorbed by $S^f_{T_c}$ is $Pc * \Delta Qc > 0$
- The power absorbed by $S^e_{T_h}$ is $\Delta Ph * Qc > 0$

An energy flow between $S^f_{T_c}$ and $S^e_{T_h}$ imposes that one source supplies power. In this case bond graph conventions (cf. half arrows) are broken, so this process cofunction is not acceptable: it does not represent any energy flow between a source and a sink. To construct a process cofunction which corresponds to a real energy flow we need:

1. to respect causality, as described in the previous section
2. to verify that one source supplies energy flow (the arrow points from the source to the junction) and the other source consumes energy (the arrow points from the junction to the source).

If a capacitor or an inductor is involved in the cofunction the second point does not need to be verified because such an element does not impose the orientation of the power flow. The direction of the energy flow in the process is given by the direction of the source energy flow (on the bond).

Automatic construction of process cofunction

A process must correspond to a power flow between a source and a sink. To construct such a process we must follow a path in the bond graph respecting the causality imposed by the elements and the junctions.

The construction of the cofunction is done by the following algorithm:

1. We start from any source of power flow (positive power from the source element to the junction). The corresponding bond graph element may be an effort or a flow source, a capacitor or an inductor releasing energy. The corresponding functional role is the first functional role of the process cofunction (G^e, G^f, R^q or R^p).

2. From this first element we build all the paths through the junctions following either the effort or the flow according to the imposed causality. In other words, through a junction (without any connected resistor) if the path enters through a bond imposing an effort (resp. a flow), it must exit through a bond imposing an effort (resp. a flow) on the next element (or junction). The path ends with a source (sink), a capacitor or an inductor.

3. If a resistor is connected to a crossed junction two cases are possible: (a) The resistor is a purely dissipative element (figure 6). It is added to the cofunction as a conduit (C^f at the top of figure 6 and C^e at the bottom). (b) The resistor is in fact a regulative element (figure 7). It is added to the cofunction as a conduit (C^f at left and C^e at right) and the causality respected by the path is changed: if the path enters through a bond imposing an effort (resp. a flow), it must exit through a bond imposing a flow (resp. an effort) on the next element.

   There is another case where the causality respected by the path is changed. It is when the path crosses over a gyrator. The gyrator is added to the cofunction as a purely conductive conduit (CC).

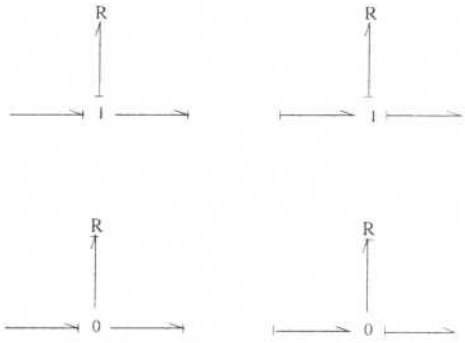

Figure 6: Dissipative resistor cases

4. As described previously, a path must end with a source playing the role of a sink (positive power from the junction to the source element) or a storage element. But, as for any junction, building the other candidate paths must be continued.

Figure 7: Regulative resistor cases

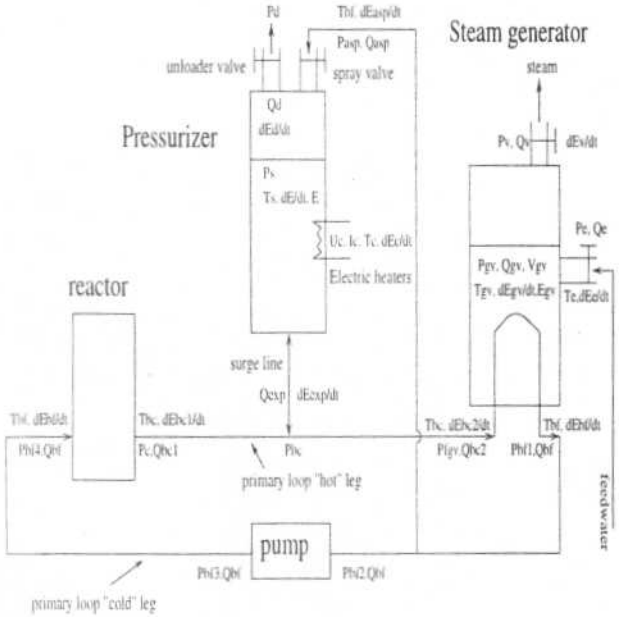

Figure 8: PWR Primary Coolant Loop

Example

The algorithm is illustrated on the hydraulic part of the PWR primary coolant loop. The PWR primary coolant loop (figure 8) is composed of the reactor where the water is heated, the pressurizer which forces the effort at an imposed value, the steam generator where energy flow is transferred from the primary loop to the secondary loop, a pump and pipes connecting these different components. In figure 9 we present a bond graph of the PWR primary coolant loop where the pressurizer, the pump and all the pipes (resistors) have been removed in order to simplify the presentation. In this bond graph there are four sources (including two sinks), a capacitor and an inductor. The sources are $S_f(T_h)$ and $S_e(T_c)$ and the sinks are $S_f(T_c)$ and $S_e(T_h)$. The first source $S_f(T_h)$ corresponds to the expansion of the water created by heating: its effect is to increase the volume flow rate in the "hot" leg. The source $S_e(T_c)$ corresponds to the effect of the gravity (the density of the cold water is greater than the density of the hot water): its effect is to increase the effort in the "cold" leg. The source (sink) $S_f(T_c)$ corresponds to the contraction of the water created by cooling: its effect is to decrease the volume flow rate in the "cold" leg. The source (sink) $S_e(T_h)$ corresponds to the resistive effect of the gravity (the density of the hot water is smaller than the density

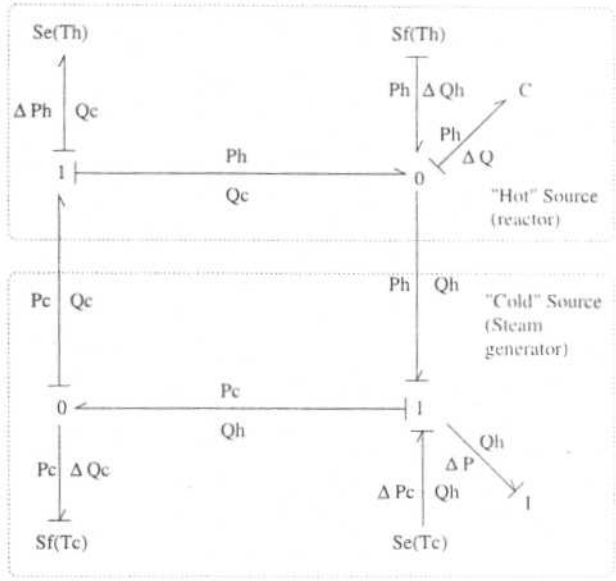

Figure 9: Simplified Bond graph of the hydraulic part of the PWR primary coolant loop

of the cold water): its effect is to decrease the effort in the "hot" leg. The capacitor C corresponds to a water volume storage in the primary coolant loop and the inertance I corresponds to a water mass storage. According to the functional role model constructed from the bond graph in figure 9 we can construct six processes, starting from the sources $S_f(T_h)$ and $S_e(T_c)$ then from C and I.

- Process P_1: From the source $S_f(T_h)$ the only possible path following the flow, through the 0-junction, is toward C. The cofunction of P_1 is $G^f(T_h) - R^q$. P_1 corresponds to the increase of the relative volume due to the expansion of water and represents storage of potential energy.
- Process P_2: From the source $S_e(T_c)$ the only possible path following the flow, through the 1-junction, is toward I. The cofunction of P_2 is $G^e(T_c) - R^p$. P_2 represents storage of kinetic energy due to the gravity effect.
- Process P_3: From the capacitor C two possible paths following the flow are possible. The first one takes the bond P_h/Q_h. After this, the only possible path through the 1-junction, is toward I. The cofunction of P_3 is $R^q - R^p$. P_3 represents the energy flow from the capacitor to the inductor and it transforms potential energy into kinetic energy.
- Process P_4: The second path starting from the capacitor C takes the bond P_h/Q_c. After this, through the 1-junction, one of the two possibilities is to take the bond P_c/Q_c and next, through the 0-junction, we take the bond toward $S_f(T_c)$. The cofunction of P_4 is $R^q - G^f(T_c)$. P_4 represents dissipation of potential energy due to cooling.

- Process P_5: From the inductor I the only remaining possible path following the flow, through the 1-junction, takes the bond P_c/Q_h. After this, through the 0-junction, the only possibility is to take the bond P_c/Q_c. Through the 1-junction, one possibility is to take the bond $\Delta P_h/Q_c$ toward $S_e(T_h)$. The cofunction of P_5 is $R^p - G^e(T_h)$. P_5 represents dissipation of kinetic energy due to the gravity resistive work.
- Process P_6: From the inductor I we follow the same path as above until the 1-junction connected to $S_e(T_h)$ where we take the remaining bond P_h/Q_c, then through the 0-junction the only possible path is toward C. The cofunction P_6 is $R^p - R^q$. P_6 represents an energy flow from the inductor to the capacitor and transforms kinetic energy into potential energy.

Note: The algorithm finds two other process cofunctions (P_3' and P_5') corresponding to the reverse cofunction of P_3 and P_5. These processes do not exist in the PWR coolant loop. They are found because the bond graph, used as an example, is oversimplified. It does not take into account all the components and the physical phenomena of the loop.

Conclusion and perspectives

Process cofunctions can be constructed easily, with our method, whenever the bond graph is done but processes are defined mainly by their cofunctions and their preconditions, effects and post-effects. The next step for automatic construction of processes is the direct derivation of these preconditions, effects and post-effects from the bond graph. Preconditions correspond to power imbalance conditions because a power flow on a bond is defined by the power imbalance causing (according to bond graph causality) the power flow in this bond. In the bond graph, these balances correspond to effort (1-junction) or flow (0-junction) balances, which is clearly related to the preconditions proposed in (Chittaro *et al.* 1993). Effects result of the imbalance of power. The storage elements (capacitor or inductance) force us to take into account the sign of the first derivative of effort and flow variables, so we must identify the storage elements dynamics. This point is slightly connected to the work described in (Mosterman, Biswas, & Narasimhan 1997) but with a functional approach of the system.

The process model, which is constructed from this set of processes, is used in two major ways. In a first step, we are using this approach to interpret the correct behavior of a system. In particular, we are trying to define the relationship between processes: which processes are competing with other ones, how processes cooperate, which (and how) process can interrupt another one, etc... So, we will be able to explain the behavior of a system across the time, knowing which processes are active and how they interact. In a next step, we will use this approach to solve diagnosis problem, mainly to reduce the expansive computational cost of Model Based Diagnosis. The detection step, identifying the discrepancies between predicted and observed behaviors, allows one to determine the processes which must be active but are actually inactive. The cofunctions of these processes localize the failing functional roles of the components and can be used to focus the isolation step of a diagnosis algorithm. The methods based on the multimodeling approach for interpreting or for diagnosing systems can usefully rely upon this automatic construction of processes (Thétiot, Zouaoui, & Dumas 1997).

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