Katholieke Universiteit Leuven

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ESAT-SISTA/TR 1996-42

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October 1996
Accepted for publication in the 1997 International Conference on Bond Graph Modeling and Simulation, Part of the 1997 Western Multiconference, Phoenix, Arizona, USA

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This work is supported by several institutions: the Flemish Government (Concerted Research Action MIPS, ICCoS, IWT/VCST project design of an electronically controlled Continuous Variable Transmission (1992-1997)), the Belgian Government (IUAP-17 (1991-1995), and IUAP-50 (1992-1996)), and the European Commission (Human Capital and Mobility Network SIMONET, and SCIENCE-ERNSI SC1-CT92-0779).

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Keywords: bond graph methodology, physical systems modeling, structured modeling, model analysis.

ABSTRACT

This paper presents an improved bond graph modeling method, called *condensed bond graph modeling.* This method makes full use of the benefits of bond graphs: their ability to structure the knowledge of a system and to visualize graphically all kinds of physical laws. Before this improved modeling method can be used, some lacks in the language definition of bond graphs have to be eliminated. The resulting bond graphs are perfectly downward compatible. The two major differences with classical bond graphing is the exclusive use of generalized pre-causal definitions and normal representations of bond graph components. All this can be done without using complicated or unnatural conventions.

1. INTRODUCTION AND PROBLEM STATEMENT

Bond graphs focus the attention on power as primal concept in the translation of a physical system to a mathematical description [Minten *et al.* 1996/2]. In order to be useful, the graphical components of a bond graph must be defined unambiguously, both syntactically and semantically.

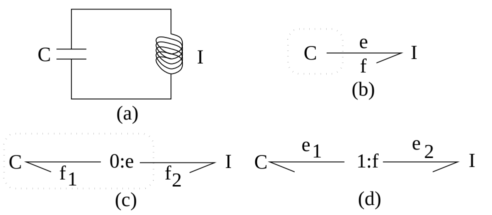

Figure 1: a simple electrical circuit and three valid bond graph representations

Consider the example of a simple passive electrical circuit, depicted in Figure 1. The three quite common bond graph models shown in Figure 1 (b) to (d), are valid representations of the electrical circuit. The bond graph on the top represents a power transfer from the capacitor to the conductor, the bond graph on the lower left indicates a common effort, and the bond graph on the lower right indicates a common flow. However, the final mathematical model should be the same since one deals with the same circuit. Hence different governing equations should be used in the different bond graphs. It is hard to choose the right equations having only the knowledge offered by the bond graph. One has to look back at the circuit. One even has to modify it in order to know exactly (1) which equations, (2) which parameters and (3) which bond graph one should use. Finally one also needs to recall the circuit to determine what the meaning of the used variables are. This is a *backtracking trace* in the modeling process. Such uncomfortable backtracking traces can be avoided if one has a clear interpretation of what has been written in the bond graph. To avoid backtracking, the mapping of, on the one hand the mathematics and, on the other hand the physics into the bond graph must be unambiguous. In the example of Figure 1, references of the power variables should be placed on the circuit [Perelson 1975]. However, this does not eliminate all of the backtracking traces since, in other practical situations there still remain some ambiguities.

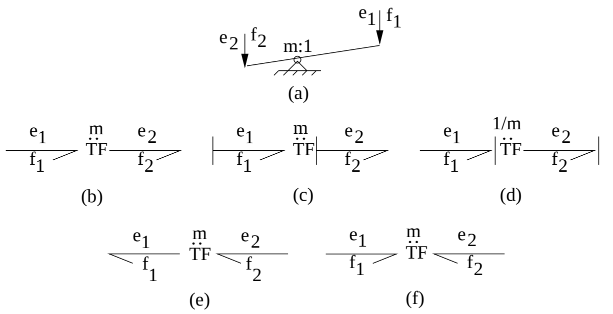

Figure 2: (a) a lever, represented as a two-port transformer (b) to (f). Three different views on power transfer are shown in (b), (e) and (f). Two possible causal augmentations of the first one are shown in (c) and (d)

Take for example the simple lever mechanism shown in Figure 2 (a) and some of its bond graph representations (b) to (f). The question can be raised whether these bond graphs represent unambiguously the same physical model augmented with reference power variable directions? Again, the answer is no. None of the proposed bond graph models is able to represent the lever without raising questions about the meaning of some parameters. These kind of ambiguities flood the bond graph literature, some of which are found in e.g. [Rosenberg and Karnopp 1972, Karnopp *et al.* 1990, Cellier 1991, Ljung and Glad 1994]. Hence, in practice, even with the use of proper power variable references, equations and parameters should be re-invented and the physical model should probably be altered again. Once again some inefficient backtracking traces will disfigure the modeling process.

Clearly, some deficiencies in the bond graph language definition are not very well understood, or permit to result in such ambiguous situations. It has been shown in [Minten *et al.* 1996/1] that, for scalar bond graphs (i.e. bond graphs which do not include multi-port components except for 2-port power continuous transducers and 0- and 1-junctions), it is perfectly possible to maintain the compactness of the bond graph method and to avoid simultaneously syntactical and semantical ambiguities. In order to obtain this, pre-causal definitions of bond graph parameters and normal representations of bond graph symbols have to be used. The resulting bond graph is called *condensed* since it contains graphically *more* unambiguous information of the physical model than the common bond graph. It is the aim of this paper to present this kind of bond graph in the modeling process of physical dynamic systems. It will be shown that this method improves the efficiency and robustness of the modeling process.

The paper is organized as follows: For sake of clarity Section 2 presents the pre-causal definitions, the physical semantics of the power variables and the bond graph parameters, and the normal representations of bond graph symbols. In Section 3 the condensed bond graph modeling method is proposed. In Section 4 two simple, yet informative examples will illustrate the benefits of the method, and finally in Section 5 some conclusions are drawn.

2. PROPOSITIONS

Due to space limitations the user is referred to the appropriate literature [Karnopp *et al.* 1990, Paynter 1992, Breedveld 1986, Thoma 1991, Minten *et al.* 1996/1, Minten *et al.* 1996/2] for supplementary background information or generalizations of the propositions made. After each definition or property some comments are given to broaden the physical interpretation.

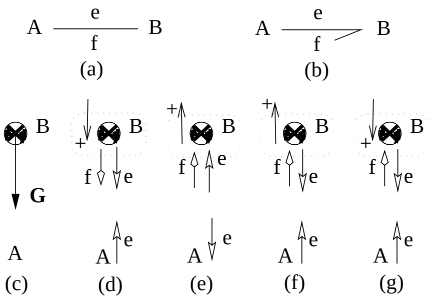

Figure 3: (a) a (power) bond representing power interaction between two elements A and B, (b) a signed or directed bond, (c) a point mass in a gravity field, (d) to (g) a free body diagram (dashed box) of the point mass illustrating the power transfer

Definition 1 *(Figure 3 (a)) The power transfer between two components is visualized as a bond connecting the power ports of the corresponding components. This can be defined as*

$$P \stackrel{\text{def}}{=} e \cdot f \qquad (1)$$

with e the effort and f the flow variable. Both are power bond *variables. Since such a bond reflects the power transfer, it obeys power continuity, i.e. energy conservation in time and space.*

Such a bond is extremely useful in high level modeling where, in general, no references are defined. Note that these power bond variables are not equal to the power *port* variables, known as the across and through variables, since their definition is different.

Property 1 *(Figure 3 (b)) A directed or signed bond is represented by a harpoon connected to one side of the bond. According to Eqn. (1) such a signed bond is intimately connected with the power variables reference directions proposed in the physical model.*

Initially, when creating a bond, the shown power variables of the bond can be seen as the reference variables in the physical model. Hence, they define a coordinate system of the power space of the physical model. Later on, e.g. during a simulation, these variables are interpreted as the coordinates in the power space. Their values can change sign indicating an opposite direction with respect to the original reference direction.

Property 2 *The power continuity property of the bond automatically imposes the continuity and compatibility laws of physics.*

Since a bond *connects* components, the general connection conditions, i.e. the continuity and compatibility laws, are valid for the bond variables. Continuity laws involve through variables, compatibility laws involve across variables. Examples of the continuity laws are Newton's third law (action-reaction law in mechanics) and the K.C.L. (Kirchoff Current Law in circuits). Examples of the compatibility laws are the geometrical connection constraints (mechanics) and the K.V.L. (Kirchoff Voltage Law in circuits). This makes it possible to build-in the conservation laws in the notation of the bond. A small example illustrating their important physical implications is given in Figure 3 (c) to (e). In Figure 3 (b) A represents a gravity source (earth) and B a point mass. The point mass experiences a positive valued reference effort $+e$ at its power port and the gravity source experiences a negative valued reference effort $-e$ at its power port. The signs + and $-$ stem from the harpoon direction and are in agreement with the free body diagrams of Figure 3 (d) and (e). Moreover, the power transfer to the point mass is $P_{E \rightarrow M} = +(e \cdot f)$, the power transfer to the gravity source is $P_{M \rightarrow E} = -(e \cdot f)$, with $P_{M \rightarrow E}$ denoting the power transfer from the point mass to the earth, and $P_{E \rightarrow M}$ denoting the power transfer from the earth to the point mass. Here the signs also stem from the harpoon arrow and are also in agreement with the free body diagrams of Figure 3 (d) and (e). Hence the interpretation of the directed bond is in accordance with the physics. Consequently, in translational mechanics, one can interpret the reference efforts as reference external forces acting on the component, and this with a direction governed by the harpoon direction. Hence, in mechanics the reference power arrow direction (harpoon) is also the direction of the reference effort variable. Remark that it should be clear that Figure 3 (f) and (g) are not valid physical models of the point mass represented as B in the bond graph of Figure 3 (b).
In electrical circuits, the same holds for the reference flow variable.

Definition 2 *The flow variable is put on the side of the harpoon (harpoon rule).*

This arbitrary choice has been made to get rid of ambiguous interpretations of the bond variables at a bond. Since for non-mechanical systems, the direction of the bond imposes both the direction of the reference power and the reference flow (see Property 2), there is some physical meaning behind this choice (at least for non-mechanical systems).

Property 3 *The power continuity property is valid for every power continuous component of the junction structure, i.e. TF, GY, 0- and 1-junctions.*

Consequently, a collection of junction structure components is also power continuous.

Definition 3 *The normal forms of bond graph components are the following:*

1. *Storage components and passive dissipators have inward sign conventions, i.e. the harpoons are directed to their power ports.*
2. *Source components have in general outward sign conventions, i.e. the harpoons are in general not directed to their power ports.*
3. *Two-port power continuous transducers have the through sign convention, i.e. exactly one harpoon is directed to one power port of the transducer.*

This has several consequences, all quite natural, what explains the name *normal form*. Three of them are:

1. Two-port power continuous transducers behave at one side as inward, and at the other side as outward, visualizing the power transfer from one to another domain. In that case the transducer parameter gain is unique. For example, for a transformer in normal form it can be deduced from Property 2 that

$$\begin{cases} e_1 = m \cdot e_2 \\ f_2 = m \cdot f_1 \end{cases} \tag{2}$$

revealing a unique gain m. Hence, this can be represented unambiguously in the bond graph.

2. According to Eqn. (1), the reference power variables of inward signed components have the same direction and the reference power variables of outward signed components have opposite directions.

3. The combination of Property 1 and Definition 3 allows in the modeling process the use of a simple reference direction in each part of the physical system separated by power continuous transducers and/or sources; a flow reference with respect to *an inertial frame* in the mechanical domain and an effort reference with respect to a *datum node* in other domains.

Definition 4 *A physical model that contains the necessary references of the power variables is called* an augmented physical model.

Such an augmented physical model is the key step in the development of a condensed bond graph.

Definition 5 *The embedded constraint equations are the equations representing the laws of continuity and compatibility of the junction structure of a physical model.*

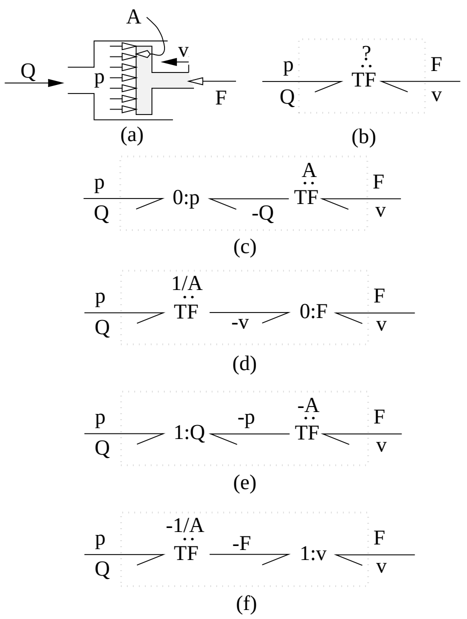

Figure 4: A hydraulic cylinder. The physical model (a) forces the TF to have the two power arrows directed towards the TF field, shown in (b). This non-normal form can be converted into a normal one by means of tearing, shown in (c) to (f)

Take for example a hydraulic cylinder and its corresponding bond graph, shown in Figure 4 (a) and (b). The references of the power variables force the transformer to have the inward sign representation. Such a bond graph is not capable of making a difference between the two power ports. Hence, the gain equations (Eqn. (2)) cannot be used since a unique modulus fails to describe the transformer behavior. Therefore, the embedded constraint equations offer means for a proper assignment of a bond graph to a physical model. This is based on Property 3. The continuity law applied to the physical model imposes

$$A \cdot p = F \tag{3}$$

(both efforts are to be viewed as external efforts acting on the TF, see Property 2), and the compatibility law imposes

$$\frac{1}{-A} \cdot Q = v. \tag{4}$$

Therefore, in mechanical systems the continuity law can be called the *effort equilibrium equation* and the compatibility law can be called the *flow continuity equation.* These two equations are called the embedded constraint equations of the IPM. The fact that different gains are ruling the transformer behavior results in the question mark in the bond graph.

Property 4 *Non-normal realizations of bond graph components can be made normal by tearing a* 0*- or* 1*-junction out of the component.*

Non-normal representations occur when the continuity and compatibility laws of a connection are not explicitly present at a bond. An example of a non-normal storage component is already shown in Figure 1 (b). The capacitor encircled by a dashed box has an outward sign convention. To obtain the inward sign convention, one of the reference power variables has to be reversed *internally.* This can for example be achieved by introducing a 0-junction, as has been done in Figure 1 (c). At the physical power port every reference port variable remains the same ($f_2 = f$, and e). Internally however, i.e. inside the dashed box, the flow and field parameter will change sign. Consequently, the teared 0-junction shows the continuity and compatibility law explicitly. This information was only implicitly available in the single bond.
Figure 2 (f) shows another example of a non-normal form. The inward signed transformer is in agreement with the reference variables shown in the physical model. In some situations it is perfectly possible to change the direction of one of the reference power variables in the physical model. Simultaneously, the direction of the corresponding reference power arrow will change in the bond graph. However, due to external constraints, the references of the physical model can sometimes not be changed. Figure 4 (c) to (f) shows how the tearing mechanism works for the hydraulic cylinder. Four possible normal representations are obtained. It is clear the the forms with the most natural modulus is preferable, i.e. Figure 4 (c) and (d). The embedded constraint equations, Eqns. (3) and (4), guide in this choice.

Definition 6 *The component parameter (function) is constrained by its normal representation and by the reference power variables of the bonds which are connected to the power gates of the component, e.g.:*

1. *For a linear dissipator we have*

$$R \stackrel{\text{def}}{=} \frac{e}{f}, \tag{5}$$

2. *For a linear storage component we have*

$$storage\_parameter \stackrel{\text{def}}{=} \frac{extensive\_variable}{intensive\_variable} \tag{6}$$

Depending on the type of storage component (e.g. kinetic and magnetic resp. potential and electric), the generalized extensive variable (energetic or state variable) is $p = \int e \cdot dt$ *(momentum) or* $q = \int f \cdot dt$ *(displacement). The corresponding generalized intensive variable is* f *(flow) or* e *(effort).*

3. For a linear transformer we have

$$m \stackrel{\text{def}}{=} \frac{e_1}{e_2} \tag{7}$$

and for a linear gyrator we have

$$r \stackrel{\text{def}}{=} \frac{e_1}{f_2} \tag{8}$$

The index 1 *corresponds to the unique bond with the power arrow directed towards a power port of the transducer.*

4. The definitions for dissipators, hold as well for the sources. The parameter symbol changes from R *into* s*.*

5. A 1*-junction has the common flow* f *as parameter, a* 0*-junction has the common effort* e *as parameter.*

These parameter symbols are written beside the component symbol, spaced by a colon.

3. OUTLINE OF THE METHOD

In this part, the bond graph should be interpreted as an intermediate model towards a final, more mathematically tractable description of a physical system. Therefore, the more useful information about the physical system is explicitly included in the graph, the less the modeler risks to meet backtracking traces in the modeling process, and hence, the more the efficiency is increased. It should be noted that for simple physical models, the proposed model generation seems overkill. But again, even in this case the reader should consult the literature to get convinced of the need for an unambiguous graphical representation of a system to be modeled. This generic procedure excludes some modeling ambiguities of the systematic procedure proposed by [Breedveld 1986] by means of four improvements: (1) for scalar bond graphs the parameter ambiguities are excluded by the exclusive use of normal representations and proper definitions, (2) the use of the T-construct is modified to have a better treatment of the ideal components, (3) the procedure is generalized towards the unambiguous treatment of general nonlinear bond graph components, and (4) the treatment of the sub-domain power connections is done in a more structured fashion. These improvements are mainly based on a better exploitation of the bond properties (proposed in Section 2) in the modeling process. The procedure also avoids explicit tearing.

1. **Identification of the physical sub-domains of the IPM** (Ideal Physical Model)**:**
   Identify all physical sub-domains and its ideal components. The inter-sub-domain boundaries involving power transfer are the power continuous transducers. The other sub-domain boundaries involving power transfer are the sources. Note that within one sub-domain there also can occur power continuous transducers.
2. **Augmentation of the IPM:**
   Choose a proper reference in each sub-domain. It is a good habit to choose every sub-domain reference according to the 'normal' power flow in that sub-domain.
   1. *For non-mechanical sub-domains:* choose a sub-domain reference effort ('datum node' in electrical circuits), and locate the necessary effort differences throughout the sub-domains with respect to the sub-domain reference effort. As a rule of thumb, choose as datum node a reference effort that is common to the maximum number of components. In most cases (always in the linear case) this choice results in a bond graph with a compact junction structure.
   2. *For mechanical sub-domains:* choose a sub-domain reference flow direction (an 'inertial frame'), and show the necessary flows throughout the sub-domains with respect to the sub-domain reference flow.
3. **Bond graph generation of the sub-domains:**

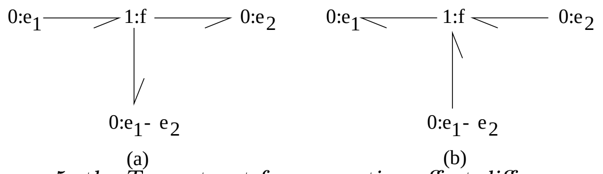

Figure 5: the T-construct for generating effort differences, (a) for inward signed and (b) for outward signed components

   1. *For non-mechanical sub-domains:*
      It is not necessary to know explicitly the component reference power variables before the next two steps are finished.
      1. Except for the sub-domain reference effort, represent all the existing efforts of the IPM by 0-junctions. Maintain if possible the same topological position.
      2. Create the necessary effort differences by means of the T-construct shown in Figure 5. Choose Figure 5 (a) for inward signed components, and Figure 5 (b) for outward signed components. This makes it possible to visualize explicitly the continuity law, which in turn makes it possible to simplify considerably the bond graph in the final step 4.
      3. Connect the efforts (i.e. 0-junctions) of the bonds of the normal components to the corresponding efforts obtained in the previous step, and indicate the field parameter with use of the colon. For nonlinear non-odd components (hence including ideal sources, and consequently also including the power continuous transducers) invoke eventually a sign reversal of the efforts by means of interfacing the 0-junctions by a two-port 1-junction with opposite power arrow directions, showing for example explicitly the flow of the bond of the component to be attached.
   2. *For mechanical sub-domains:* dual, i.e. use 1-junctions instead of 0-junctions.
4. **Simplify** the bond graph by deleting redundant junction structure constructs, i.e. 2-port 0- and 1-junctions with a through sign reference.

(5. Proceed with the appropriate augmentation of the bond graph.)

4. EXAMPLES

The bond graph modeling process shown below follows the same steps as mentioned in the outline, Section 3.

A. A Nonlinear Electrical Circuit Example

This example is inspired by [Chua *et al.* 1987] pp.63. In Figure 6 (a) the IPM and the nonlinear port characteristics of the resistors are shown. Thereafter, in Figure 6 (b) the condensed bond graph modeling procedure is applied to this example. Remark that the continuity law is explicitly used in step 3.1.2. (common flow i), resulting in a bond graph to which straightforward simplifications can be applied in step 4. Notice e.g. that the port variable v_1 of the resistor R_1, denoted as bond variable v_1 is not equal to the bond variable $e_{12} = e_1 - e_2$ in step 3.1.3. Hence this connection is interfaced with a 1-junction showing the port current i_1 as common flow.

If the continuity laws aren't used explicitly, then a slightly different bond graph will be achieved, as shown in Figure 6 (c). This kind of bond graph reveals more a port modeling methodology (signal based, like system or linear graph methods) than a bond modeling methodology (power based, like a bond graph). Because in a port modeling method the continuity and compatibility laws of the connections are not explicitly available, and because bond graphs have just the ability to represent them explicitly by the bond properties (Property 2), more junction components appear in this port based bond graph.

B. An Electro-Mechanical Example

In Figure 7 (a) the IPM of an electro-mechanical active suspension is given, and in (b) the characteristics of an ideal linear motor are shown. Here F_{lm} represents the equilibrium mechanical force against the force originating from i_{lm}, i.e. the electro-magnetical force of the linear motor. Hence this force should be interpreted as an external force with magnitude $F_{lm} = r \cdot i_{lm}$. In Figure 7 (c) the major steps of the condensed bond graph modeling procedure are shown. The reference direction of the mechanical subdomain on the left has been chosen such that there is a positive reference power entry at the effort source $F(t)$. Since as always $F(t)$ is to be interpreted as an external force acting on the mechanical subdomain, the reference direction is directed in the same sense. The reference power is further transmitted downward resulting in a flow (difference) $v_{12} = v_1 - v_2$. Since spring k_1 and dissipator d are linear and hence odd they can be attached directly to this 1-junction v_{12}. The same motivation holds for the other linear components, except from the subdomain boundaries represented as sources and power continuous transducers. Since no active source (active means modulated by a control signal) is present in the mechanical subdomain in the middle, the reference flow in that part of the system is chosen such that the normal representation of the lever (TF) and the compatibility conditions are achieved. Hence normal power flow is chosen from left to right, and it follows that according to Eqn. (7), $m = \frac{b}{a}$. Remains the connection of the second mechanical subdomain in the middle with the electrical subdomain on the right. In that domain also an active voltage source $u(t)$ pushes energy in the system, and the reference direction of the electrical domain is chosen accordingly. Hence the gyrator will have a non-normal representation since the reference power directions at both sides will enter the gyrator. To avoid explicit tearing, the gyrator is forced to have normal representation in the augmented IPM. Here, the reference power transfer is chosen arbitrary from right to left, which implies in the augmented IPM of the gyrator an equal direction of the reference power variables at the electrical side (e_{lm} and i_{lm} inward) and an opposite direction of the reference flow v_{lm} with respect to F_{lm} at the mechanical side. Hence the compatibility of the overall connection urges for an interface between the reference flows v_4 and v_{lm} by means of a two-port 0-junction with opposite power arrows, showing for example the linear motor force F_{lm}.

It is left for the reader to verify Property 2 for this example.

5. CONCLUSIONS

This paper has focussed the attention on the need for an unambiguous and systematic method for the bond graph modeling process. It has been shown that ambiguities break down the efficiency and robustness of the power bond modeling process. To solve this, first some essentials about the physical semantics of a power bond and the power variables are discussed, then pre-causal definitions of bond graph parameters and normal representations are proposed, and finally Breedveld's systematic method has been optimized with use of the condensed bond graph. The benefits of *condensed bond graphing* are manifold. Four of them are (1) the explicit visualization of the continuity and compatibility laws of the connections resulting in a compact junction structure, (2) the vanishing of some existing ambiguities of the formal bond graph language, (3) the fact that the bond graph gets more informative and more portable to other people, and (4) the modeling process of scalar bond graphs becomes more efficient, structured and comprehensive, since no backtracking traces are encountered any more. Hence, it improves the design process of physical dynamic systems with bond graphs.

ACKNOWLEDGMENTS

This work is supported by several institutions: the Flemish Government (Concerted Research Action MIPS, ICCoS, IWT/VCST project design of an electronically controlled Continuous Variable Transmission (1992-1997)), the Belgian Government (IUAP-17 (1991-1995), and IUAP-50 (1992-1996)), and the European Commission (Human Capital and Mobility Network SIMONET, and SCIENCE-ERNSI SC1-CT92-0779).

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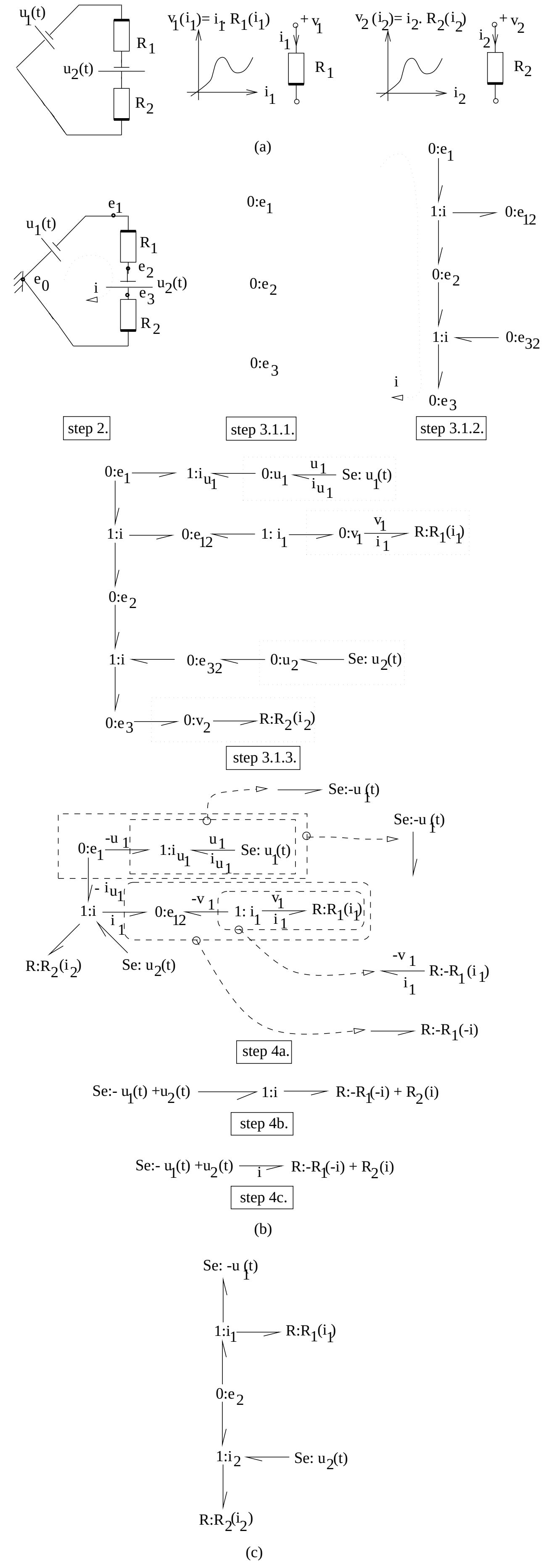

Figure 6: condensed bond graph modeling: a nonlinear electrical example

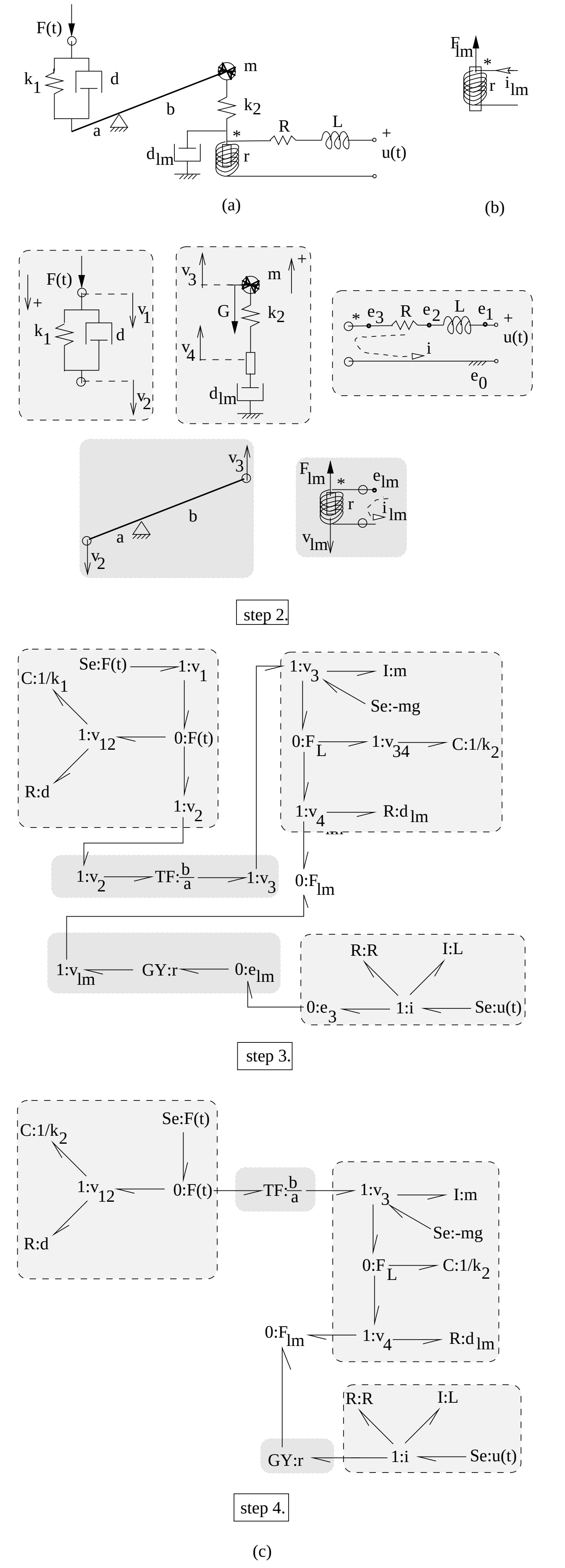

Figure 7: condensed bond graph modeling: an electro-mechanical example