Available online at www.sciencedirect.com
ScienceDirect
Simulation Modelling Practice and Theory 17 (2009) 152–174
SIMULATION MODELLING PRACTICE AND THEORY
www.elsevier.com/locate/simpat

Energy shaping, interconnection and damping assignment, and integral control in the bond graph domain

Alejandro Donaire [a,b,*], Sergio Junco [a]

[a] Departamento de Electrónica – Universidad Nacional de Rosario, Riobamba 245 bis, S2000EKE Rosario, Argentina
[b] Consejo Nacional de Investigaciones Científicas y Técnicas – CONICET, 27 de Febrero 210 bis, S2000EZP Rosario, Argentina

Received 23 April 2007; received in revised form 7 February 2008; accepted 28 February 2008
Available online 7 March 2008

Abstract

This paper presents a methodology to perform energy shaping and interconnection and damping assignment in the bond graph domain, and addresses a new result on integral action control which improves the robustness of these passivity based control methods, which were first introduced on the port-controlled Hamiltonian systems with dissipation formalism. The methods perform expressing the desired closed-loop energy, interconnection and damping properties on a so-called target bond graph, which is built as follows on the plant bond graph: (i) adding virtual storage elements enforces a minimum on the target bond graph energy at a prespecified stable closed-loop equilibrium state, (ii) changing the ***R***-field and its interconnection with the rest of the graph assigns a new dissipation function, and (iii) suitably inserting of power conserving elements (bonds and other structural BG-elements) among junctions yields the desired power conserving interconnection structure. The control law is then determined developing physically based heuristics and formal techniques on the target and plant bond graphs, which deliver a set of partial differential equations to be solved. The method to achieve integral control consists in adding to the target bond graph virtual elements representing the integral action and a change of variables, and then computing the integral control law with standard BG equation-reading procedures. These BG heuristics and prototyping allow to provide integral action on outputs of relative degree greater than one, a contribution of this work not previously available in the literature. This shows that the physical properties of bond graphs are beneficial not only to expediently perform methods contributed by control theory, but also to derive new theoretical results.

Keywords: Bond graphs; Port-controlled Hamiltonian systems; Nonlinear control; Energy shaping; Interconnection and damping assignment; Integral action

1. Introduction

Port-controlled Hamiltonian systems with dissipation or PCHD, also known as input-state-output port-Hamiltonian systems [23], are most suitable for nonlinear control system synthesis based in passivity theory

* Corresponding author. Address: Departamento de Electrónica, Facultad de Ingeniería, Universidad Nacional de Rosario, Riobamba 245 bis, S2000EKE Rosario, Argentina. Tel.: +54 341 4808543x106; fax: +54 341 4802654.
E-mail addresses: adonaire@fceia.unr.edu.ar (A. Donaire), sjunco@fceia.unr.edu.ar (S. Junco).

1569-190X/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.simpat.2008.02.012

[22,19]. Energy shaping (ES) and interconnection and damping assignment (IDA) are well-known physically oriented control theoretical methods that reached their maturity when developed on this formalism. This is due to the fact that PCHDs explicitly express the global energy storage and dissipation phenomena, as well as the global structure of power exchange in the system.

The BG method has been practically oriented developed for system modeling and simulation [14]. Essentially, any BG consists of components capturing energy processes in the system (storages, dissipators, sources and sinks) and an interconnection structure showing the energy exchange among these components through power conserving elements (bonds, junctions, transformers, gyrators), thus implementing the power continuity laws in the system. As a whole, a BG expresses the same global properties as the equivalent PCHD-model (see the companion paper in this journal [6]). But, simultaneously, it reflects all these properties at the *local* level of each component and interconnection. These physical properties make BGs most suitable for system modeling. On the other hand, as all of the BG components are endowed with mathematical expressions of their constitutive relationships, the augmentation of a BG with the computational causality conventions implicitly determines global mathematical models of the system like PCHD- and Lagrangian-models, state equations, transfer functions, among others. Formal procedures to automatically derive these models have been given, see [5,13,14,18], what allows for simulation software tools to directly integrate the conversion of BG-models into simulation code [1,2,9,17]. All these properties motivated investigating the usefulness of BGs beyond their application to system design and analysis via simulation, particularly to dynamic analysis and control system synthesis. Many results on linear and nonlinear systems are already available [4,8,10,11,26]. Being in line with this research trend, this paper is concerned with the synergy of the physically based heuristics and formal manipulation techniques featured by BGs and the formal methods of passivity based control as formulated on PCHD-models. The research is practically oriented; indeed, it intends to provide tools to develop physically consistent solutions to the automation problems faced by a control system designer team. Why should this be done on the BG? Why not simply getting the PCHD-model from the BG (using the techniques presented in the companion paper to this one [6]) and then solving on it the control problem? On the one hand, as it will be seen, the BG allows not only to apply formal techniques, but also gives clues on how to made high level decisions when solving the control problem, like choosing convenient closed-loop system energy, dissipation and interconnection structures. On the other hand, and albeit this paper concentrates on abstract and pure control problems, having their BG solutions allows to integrate them with other BG techniques (modeling, simulation, analysis), moreover, merge them together in order to be able to make control related decisions already at early stages of system design.

Results affine to this paper are reported in [3,24]. The first derives a PCHD-model of a multicellular converter from its BG and then develops a passivity based controller on this model. The second contributes a general analysis of the ES and IDA techniques from a BG perspective.

Previous results used in this paper are the correspondence between PCHD models and BGs presented in [6] (an improved and extended version of [5]), as well as the ideas of expressing the closed-loop system behavior in a so-called target bond graph (TBG) and using a virtual bond graph (VBG) to construct the TBG departing from the plant bond graph (PBG), i.e., the model of the original plant [12]. Energy shaping aiming at having a stable equilibrium at a prespecified state is performed adding storage elements in the VBG such that the attained TBG has an energy minimum at that state. The IDA method is carried out assigning a desired ***R***-field (representing the new dissipation function) and inserting power conserving elements (bonds and other structural BG-elements) among junctions in order to obtain a TBG with a suitable interconnection structure. The control law is then determined solving a set of partial differential equations derived via matching the TBG and the PBG.

An important practical issue is the robustness of the control system. A classical solution in industrial applications, where model uncertainties and disturbances deteriorate the performance of the control system, is the inclusion of integral actions in the feedback loop [15,16]. The enhancement of IDA based controllers with the addition of integral actions on the passive outputs (preserving the PCHD form and, thus, closed-loop stability) is reported in [20]. As the concerned outputs are of relative degree one, this result cannot be applied in situations where the integrator must depend on variables with relative degree greater than one. In this paper, applying a BG-prototyping technique to the TBG [12], integral action is achieved not only on the passive outputs – which are always of relative degree one – but also on coenergy variables with relative degree greater