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Bond graph based control and substructuring

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Abstract

A bond graph framework giving a unified treatment of both physical-model based control and hybrid experimental–numerical simulation (also known as real-time dynamic substructuring) is presented. The framework consists of two subsystems, one physical and one numerical, connected by a *transfer system* representing non-ideal actuators and sensors. Within this context, a two-stage design procedure is proposed: firstly, design and/or analysis of the numerical and physical subsystem interconnection as if the transfer system were not present; and secondly removal of as much as possible of the transfer system dynamics while having regard for the stability margins established in the first stage. The approach allows the use of engineering insight backed up by well-established control theory; a number of possibilities for each stage are given.

The approach is illustrated using two laboratory systems: an experimental mass-spring-damper substructured system and swing up and hold control of an inverted pendulum. Experimental results are provided in the latter case.

Keywords: Bond graphs; Physical-model based control; Substructuring; Hardware in loop simulation

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1. Introduction

Most research into control systems' design is conducted in the *mathematical* domain. One reason for this is to abstract dynamic systems in such a way that control design is generic. For example, as described in elementary textbooks [9,25], such system equations can be written in block diagram form for the purposes of control system design.

However, it can be argued that this level of abstraction actually distills out system-specific features which could have aided the design procedure using engineering intuition. An alternative approach, "Design in the Physical Domain" has been suggested by Hogan [27–29] and Sharon et al. [38]. Here the level of abstraction is a graphical physical representation which lies closer to the system physics than mathematical equations. In

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particular, the bond graph approach [5,13,20,30,34] has been suggested [12,27–29,38] as the basis for such design. Moreover, appropriate software tools are now available, including Model Transformation Tools (MTT) [33]. Following [12], we call this approach *Physical-model based control* (PMBC). Systems with *collocated* sensors and actuators can be easily controlled using such an approach [12].

However, in many cases, this collocation does not exist and the actual actuators and sensors are connected to notional collocated actuators and sensors by a *transfer system* [17,18]. Such transfer systems typically contain small delays, high relative degree or unstable zero dynamics and are thus not passive.

Real-time dynamic *substructuring* [4] is a novel experimental testing technique which can be used to test individual components of engineering systems. This type of testing has been developed from experimental testing of large scale structures using extended time scales [8,35]. The basic concept is that a complete model of the system is made by combining, in real-time, a part which is experimentally tested with a numerical model of the remainder of the system. In the fields of mechanical and aerospace engineering, physical components are often tested to either characterise or improve the design performance. Substructure testing offers a way of accurately testing non-linear components as if they were in their operating environment. Some example applications are described in [43] in connection with aerospace engineering. Similarly, hardware-in-the-loop (HWiL) is a form of component testing where physical components of the system communicate with software models which simulate the behaviour of the rest of the system – a survey is given by [36]. For the purposes of this paper, HWiL testing and substructuring will be regarded as synonymous.

Once again, the issue of non-collocation due to the presence of a transfer system is the key issue. In particular, it has been shown [40,41] that substructuring is sensitive to small time delays and methods have been developed to improve robustness [22].

The bond graph based virtual actuator approach [17], developed in the control systems context can also be applied to substructuring [23]. This paper brings together these results in a unifying bond graph framework. Moreover, a common framework for design and analysis is proposed which approaches the common problem of non-collocation due to the presence of a transfer system in a unified fashion. In particular, a two-step design procedure is proposed

1. Design the *collocated* feedback system using the standard approaches given above and analyse it using robustness methods drawn from feedback theory.
2. Design a compensator to overcome the effect of the transfer system within the context of the robustness margins derived in step 1.

The formulation gives a new perspective on control design insofar as it focusses on the problems arising from non-collocation and also gives a new perspective on substructuring by reformulating the substructuring problem as a control problem.

We use two experimental systems to illustrate our approach: one is in the substructuring area and has been discussed previously [23], the other gives some new experimental results on the swing-up and hold control of an inverted pendulum – a system commonly used to evaluate control techniques [1,31].

2. Physical-model based control and substructuring

The class of systems considered in this paper is represented by the bond graphs of Fig. 1. There are three subsystems (themselves bond graphs) which represent

Num the *numerical* subsystem implemented as *software* within a digital computer,
Phy the *physical* subsystem implemented as *hardware* in the physical world and
Tra the *transfer* system comprising sensors and actuators connecting the numerical and physical domains together with the associated control systems and signal conditioning.

The subsystems are connected by *power bonds* each of which carries an effort/flow pair [20,30]. For example, the subsystem **Phy** is associated with the effort e_p and the flow f_p and the power flow e_pf_p. In general, the bonds could be *vector* bonds corresponding to the multiple connections; but this paper considers the scalar case. The