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Holistic system modeling in mechatronics

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ABSTRACT

This paper outlines an alternative modeling scheme for mechatronic systems, as a basis for their concurrent design. The approach divides a mechatronic system into three generic subsystems, namely *generalized executive, sensory* and *control*, and links them together utilizing a combination of bond graphs and block diagrams. It considers the underlying principles of a multidisciplinary system, and studies the flow of energy and information throughout its different constituents. The first and second laws of thermodynamics are reformulated for mechatronic systems, and as a result three holistic design criteria, namely *energy, entropy* and *agility*, are defined. These criteria are formulated using the bond graph representation of a mechatronic system. As a case study, the three criteria are employed separately for concurrent design of a five degree-of-freedom industrial robot manipulator.

1. Introduction

Mechatronics is a synergistic approach to the design, development and manufacturing of multidisciplinary engineering systems, where the emphasis is on the physical integration and information communication amongst various subsystems in a holistic fashion [1]. The synergy must be rooted into how such systems are viewed as a unified physical entity, instead of a collection of several subsystems. Consequently, the criteria based on which mechatronic systems are designed and evaluated must refer to universal characteristics, in addition to specific performance indexes. In the traditional design approaches different modeling schemes are employed for the subsystems separately, and a collection of objectives are defined to be optimized given the constraints that are enforced by each individual subsystem. These approaches often undermine the interconnection between the subsystems, which can play a significant role in the overall performance of a multidisciplinary system. The necessity of collaboration and information communication amongst the subsystems of a mechatronic system highlights the importance of a holistic approach to its modeling, which is capable of viewing all the subsystems with different physical domains from a unified perspective.

In this paper a generic interpretation of mechatronic systems is introduced based on the notion of information and energy flow throughout the system. Accordingly, a combination of bond graphs and block diagrams is used to represent mechatronic systems. The analogy between mechatronic and thermodynamic systems is formalized, and the laws of thermodynamics are reformulated for defining some global design criteria that deem the system as a whole.

Several attempts have been launched to unify the dynamic equations of mechatronic systems that consist of strongly-coupled mechanical, electrical, and control components. For instance, linear graph theory has been utilized for modeling various physical systems since the mid 1960s. It was originally employed in modeling of electrical networks [2], but gradually extended to multibody systems [3], and eventually mechatronic systems [4]. This approach tries to graphically connect the topological representation of a system to the physical characteristics of engineering components. The intention is to reduce the complexity of the governing equations in a formal way. Physical variables, namely *through* (e.g. force or current) and *across* (e.g. displacement or voltage), on each edge are defined based on their methods of measurement [5]. The *terminal* relations between the variables and the system topology are used to extract a system of mixed differential and algebraic equations in a matrix form [6].

Alternatively, in the early 60s the concept of energy and energy exchange was realized as a common notion to all components of a system with different physical disciplines [7]. Later, the concept of port in electrical circuits was generalized to power port, labeled as *power bond*, in an arbitrary physical domain [8]. The resulting modeling scheme, called *bond graphs*, is a domain-independent graphical description of dynamical behaviour of multidisciplinary systems. Similar to the graph theoretic approach, it emphasizes that the analogy between different domains is more than the pure mathematical equations, and the actual physical concepts are analogous. Therefore, in bond graphs components of a system are recognized by the energy they supply or absorb, store or dissipate, and

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