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Mechatronics by analogy and application to legged locomotion

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ABSTRACT

A new design methodology for mechatronic systems, dubbed as Mechatronics by Analogy (MbA), is introduced. It argues that by establishing a similarity relation between a complex system and a number of simpler models it is possible to design the former using the analysis and synthesis means developed for the latter. The methodology provides a framework for concurrent engineering of complex systems while maintaining the transparency of the system behavior through making formal analogies between the system and those with more tractable dynamics. The application of the MbA methodology to the design of a monopod robot leg, called the Linkage Leg, is also presented. A series of simulations show that the dynamic behavior of the Linkage Leg is similar to that of a combination of a double pendulum and a spring-loaded inverted pendulum, based on which the system kinematic, dynamic, and control parameters can be designed concurrently.

1. Introduction

The synergistic effect of integrating different disciplines in the design of a multidisciplinary system has been documented in numerous applications, to the effect that the outcome is a new and previously unattainable set of performance characteristics e.g., [1–5]. However, the challenge in a concurrent design process is the sheer complexity of the design space with a typically large number of multidisciplinary objective and constraint functions to be taken into account simultaneously with a great number of design variables. Two approaches are suggested to address this challenge. The first is to develop better algorithms to deal with complex multidisciplinary optimizations, such as evolutionary algorithms used for parallel robot arms [6,7] and genetic algorithms used for designing reconfigurable robots [8,9], parallel manipulators [10] and mechatronic systems [11]. The second approach is to simplify the design space by approximating it through the reduction of its dimensions [12,13]. The second approach has the advantage of achieving a more transparent design process and also having the capability of better incorporating subjective design constraints at the cost of leading to approximate solutions.

This paper introduces a new methodology along the second approach to concurrent design that addresses the problem of system complexity in design by (i) finding simpler mechanisms analogous to the original complex system, (ii) optimizing such simpler mechanisms with the controller concurrently, and (iii) designing the parameters of the original system such that it behaves similarly to the simpler mechanisms with the same controller. The methodology offers qualitative and quantitative advantages over alternative methods. The qualitative advantage is that the simpler systems used for control design are real-life mechanisms, which capture non-linear effects while can be intuitively understood and studied, and additionally enjoy effective controllers already developed for them. The quantitative advantage is that the simplification of the system behavior occurs at the design level, not at the control level. As such, a higher degree of synergy can be achieved between the different subsystems.

The new methodology, called Mechatronics by Analogy (MbA), is applied to the case study of a new leg mechanism for a hopping robot. The test case is selected because legged robots offer an interesting challenge for mechatronic methodologies. In order to simplify the control of robotic legs and make the behavior more tractable and intuitive, the physical model of a leg mechanism must be simple. Simple models, such as the inverted and double pendulums are used to approximate the legs of walking robots [14], and the Spring Linear Inverted Pendulum (SLIP) model is used to approximate the behavior of running and hopping robots [15]. The behavior of such models, as well as the controllers developed for them, have been extensively studied both in the field of robotics and biological walkers and hoppers [16]. However, the control design can become far too complex, thus challenging, if the mechanical design of the legs goes beyond such simple models [17], and consequently it will be difficult to take advantage of the wealth of information already available for the simpler models.

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An overview of the MbA methodology is presented in Section 2. In Section 3, the methodology is detailed through a case study of designing a robotic Linkage Leg. A comparison with an alternative optimization method is discussed in Section 4, and some concluding remarks are made in Section 5.

2. An overview of mechatronics by analogy

The objective of Mechatronics by Analogy is to detail-design a system through (i) finding one (or more) simpler mechanism(s) that can mimic the behavior of the original system concept, (ii) developing the controller concurrently with the optimal design of such simpler mechanism(s), and finally (iii) deriving parameters of the original system such that it behaves similarly to the optimal simpler mechanism(s) with the same controller. A block diagram of the MbA methodology is shown in Fig. 1. The process begins with a desired concept of the original system, here referred to as Emulated System (ES). A bond graph model of the system is then developed, and the model is simplified based on the universal notion of energy to find a simpler mechanism, called Analogous System (AS), which relevantly emulates the ES. Next, the AS is detail-designed concurrently to find the optimal system parameters including control gains. Finally, the parameters of the ES are derived, through the dimensional analysis, such that the system optimally behaves similarly to the optimum AS. Hence, the complex task of optimizing the physical and control parameters of the ES is replaced by the task of optimizing the parameters for the AS together with the control system, and then finding the ES parameters to have a similar behavior to the optimized AS under the same controller. As it will be demonstrated in Section 4, this approach is easier to achieve, and it leads to better results than tackling the ES optimization directly, for the case of a robotic Linkage Leg design. The three main stages of the MbA are further detailed below.

The design of multidisciplinary systems usually involves varying constraints in different phases of operation. For example, in the case of legged robots when the leg is in contact with the ground (stance) the system experiences different constraints than when the leg is not in contact with the ground (swing). In this case, for each *motion phase* a separate set of constraints needs to be defined. The MbA methodology is particularly suitable for such systems with multiple motion phases. The AS can be made up of multiple mechanisms, each being a valid simplification for the ES of the corresponding motion phases. The analogous systems can be optimized independently during the *AS Optimization* stage, and then the final design of the ES is based on the combined behavior of the analogous systems.

2.1. Bond graph modeling

The first stage of MbA involves analyzing the ES and finding the simplest mechanism that represents the dynamic behavior of the original ES for each of the *N* motion phases of the ES (Fig. 2). This is done through the development of the bond graph model of the ES.

Bond graphs represent the dynamics of a system by simulating the power exchange between its components [18]. The system variables (force, velocity, current, voltage, etc.) are unified into two generalize variables, the *flow* and *effort*. The power flow between components can be computed by multiplying the flow and effort of each element. The dynamic behavior of the bond graph is computed by considering the relation between flow and effort in each element. Further, a more complex system can be represented by simpler bond graphs linked together in a modular fashion [19].

The MbA's Bond Graph Modeling stage consists of a two-step simplification. The first step, Dynamic Element Simplification (DES), eliminates the maximum number of dynamic elements while maintaining the system behavior nearly unchanged [20]. For a bond graph representing a mechanism formed by solid bodies, the dynamic elements are masses, moments of inertia, springs and dampers. For each possible combination of the system dynamic

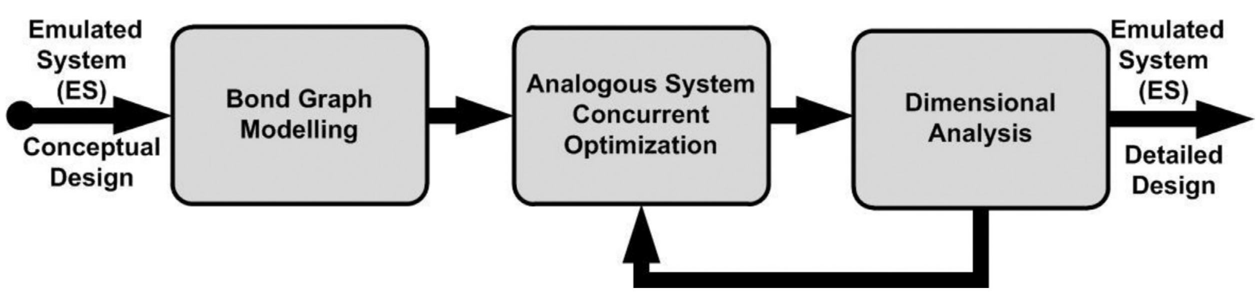

Fig. 1. Mechatronics by Analogy methodology.

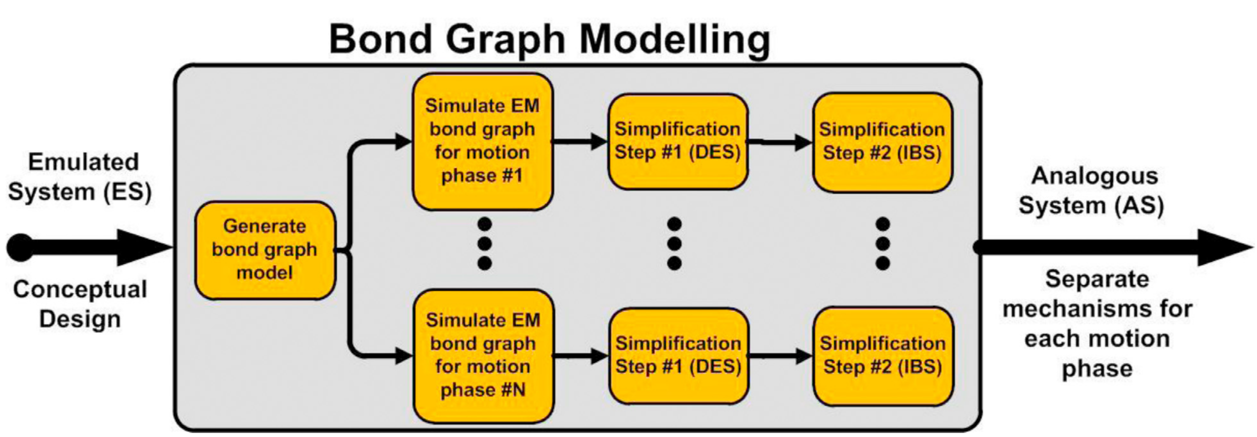

Fig. 2. Diagram of the bond graph modeling phase.

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