Physical-model-based and emulator-based control publications of Peter Gawthrop

[1] Peter J. Gawthrop. Physical model-based control: A bond graph approach. *Journal of the Franklin Institute*, 332(3):285--305, 1995. [bib | DOI]

> A bond graph representation of model-based observer control is introduced and shown to provide a convenient framework for the design of controllers in the physical domain. The approach is illustrated by a series of examples and the robustness of the method is investigated by simulation.

[2] D.W. Roberts, D.J. Ballance, and P.J. Gawthrop. Design and implementation of a bond-graph observer for robot control. *Control Engineering Practice*, 3(10):1447--1457, 1995. [bib | DOI]

> In robotics, high-precision measurements of link positions are available for feedback control but tachometer measurements of link velocities are often severely contaminated by noise. This paper presents the use of a bond-graph model-based nonlinear observer to estimate the velocities in the control of an experimental two-link manipulator. A significant advantage of this approach is that the observer software may be written automatically from the bond-graph observer representation. Results are presented in simulation form, and for practical implementation on the experimental arm.
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> Keywords: Robots, modelling, bond graphs, state estimation, position control

[3] Peter J. Gawthrop, Richard W. Jones, and Daniel G. Sbarbaro. Emulator-based control and internal model control: Complementary approaches to robust control design. *Automatica*, 32(8):1223--1227, 1996. [bib | DOI]

> Two alternative approaches to controller design, the internal model control (IMC) of Morari and Zafiriou [Morari, M. and E. Zafiriou (1989). Robust Process Control. Prentice Hall, Englewood Cliffs, NJ] and the emulator-based control (EBC) of Gawthrop [Gawthrop, P. J. (1987). Continuous-time Self-tuning Control. Vol. 1: Design, Engineering Control Series. Research Studies Press, Lechworth, U.K.] (based on the generalized minimum variance control of Clarke and Gawthrop [Clarke, D. W. and P. J. Gawthrop (1975). Self-tuning controller. Proc. IEE, 122(9), 929â934. Clarke, D. W. and P. J. Gawthrop (1979). Self-tuning control. Proc. IEE, 126(6), 640â6333. Gawthrop, P. J. (1977). Some interpretations of the self-tuning controller. Proc. IEE, 124(10), 889â894]) are shown to differ only superficially in approach and notation. This result provides a link between robust control based on IMC and adaptive control based on EBC.
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> Keywords: Control system analysis, internal model control

[4] D.J. Costello and P.J. Gawthrop. Physical-model based control: Experiments with a stirred-tank heater. *Chemical Engineering Research and Design*, 75(3):361--370, 1997. Particle Processing. [bib | DOI]

> In the pursuit of generic methods, control theory has become separated from its prime objective: the control of physical systems. These generic techniques have a wide range of applications yet do not easily allow inclusion of system specific information into the control design. There are two important categories for which the inclusion of system-specific information is important: partially-known systems and non-linear systems. Physical-Model Based Control (PMBC) is a novel approach to using such system-specific information. The objective of this paper is to demonstrate the experimental application of PMBC to a partiallyknown nonlinear system. In so doing, the performance of the PMBC method is evaluated, and it is demonstrated how process and control engineering insights can be combined within this PMBC framework to yield a novel system-specific control algorithm.
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> Keywords: state estimation, model-based control, partially-known systems

[5] Peter J. Gawthrop and Donald J. Ballance. Symbolic algebra and physical-model-based control. *Computing and Control Journal*, 8(2):70--76, April 1997. [bib | .pdf]

> In order to achieve the best possible control of a particular system, it is clear that as much information about the system as possible should be used when designing the controller. This leads to a controller specifically tailored to the system being controlled. Unfortunately, this is expensive in terms of design time and expertise, and a number of approaches have been suggested to overcome this problem. The approach taken by physical-model-based control is to model the system in a generic manner and then automatically design the controller based on this model. This process requires symbolic algebra to enable the controller to be designed

[6] Roger F Ngwompo and Peter J Gawthrop. Bond graph based simulation of nonlinear inverse systems using physical performance specifications. *Journal of the Franklin Institute*, 336(8):1225--1247, November 1999. [bib | DOI | .pdf]

> Analysis and simulation of non-linear inverse systems are sometimes necessary in the design of control systems particularly when trying to determine an input control required to achieve some predefined output specifications. But unlike physical systems which are proper, the inverse systems are very often improper leading to numerical problems in simulation as their models sometimes have a high index when written in the form of differential-algebraic equations (DAE). This paper provides an alternative approach whereby performance specifications and the physical system are combined within a single bond graph leading to a greatly simplified simulation problem.

[7] Peter J Gawthrop. Physical interpretation of inverse dynamics using bicausal bond graphs. *Journal of the Franklin Institute*, 337(6):743--769, 2000. [bib | DOI | .pdf]

> A physical interpretation of the inverse dynamics of linear and nonlinear systems is given in terms of the bond graph of the inverse system. It is argued that this interpretation yields physical insight to guide the control engineer. Examples are drawn from both robotic and process systems.

[8] Peter J. Gawthrop and Eric Ronco. Estimation and control of mechatronic systems using sensitivity bond graphs. *Control Engineering Practice*, 8(11):1237--1248, November 2000. [bib | DOI | .pdf]

> A new bond graph framework for sensitivity theory is applied to model-based predictive control, state estimation, and parameter estimation in the context of physical systems. The approach is illustrated using a nonlinear mechatronic system.

[9] Peter J Gawthrop. Bond graph based control using virtual actuators. *Proceedings of the Institution of Mechanical Engineers Pt. I: Journal of Systems and Control Engineering*, 218(4):251--268, September 2004. [bib | DOI | .pdf]

> A bond-graph based approach to design in the physical domain is described which uses the concept of virtual actuators and virtual sensors.
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> The approach is illustrated by, and implemented on, an experimental ball and beam system

[10] Peter J Gawthrop. Virtual actuators with virtual sensors. *Proceedings of the Institution of Mechanical Engineers Pt. I: Journal of Systems and Control Engineering*, 219(5):371 -- 377, August 2005. [bib | DOI]

> The virtual actuator approach to bond graph based control is extended to use virtual sensor inputs. This allows relative degree conditions on the controller to be relaxed. Furthermore, the effect of the transfer system can be eliminated from the closed loop system. Illustrative examples are given.

[11] D. Vink, D. Ballance, and P. Gawthrop. Bond graphs in model matching control. *Mathematical and Computer Modelling of Dynamical Systems*, 12(2-3):249 -- 261, 2006. [bib | DOI]

> Bond graphs are primarily used in the network modeling of lumped parameter physical systems, but controller design with this graphical technique is relatively unexplored. It is shown that bond graphs can be used as a tool for certain model matching control designs. Some basic facts on the nonlinear model matching problem are recalled. The model matching problem is then associated with a particular disturbance decoupling problem, and it is demonstrated that bicausal assignment methods for bond graphs can be applied to solve the disturbance decoupling problem as to meet the model matching objective. The adopted bond graph approach is presented through a detailed example, which shows that the obtained controller induces port-Hamiltonian error dynamics. As a result, the closed loop system has an associated standard bond graph representation, thereby rendering energy shaping and damping injection possible from within a graphical context.

[12] P. J. Gawthrop, D. W. Virden, S. A. Neild, and D. J. Wagg. Emulator-based control for actuator-based hardware-in-the-loop testing. *Control Engineering Practice*, 16(8):897--908, 2008. Available online 3 December 2007. [bib | DOI]

> Hardware-in-the-loop (HWiL) is a form of component testing where hardware components are linked with software models. In order to test mechanical components an additional transfer system is required to link the software and hardware subsystems. The transfer system typically comprises sensors and actuators and the dynamic effects of these components need to be eliminated to give accurate results. In this paper an emulator-based control strategy is presented for actuator-based HWiL. Emulator-based control can solve the twin problems of stability and fidelity caused by the unwanted transfer system (actuator) dynamics. Significantly EBC can emulate the inverse of a transfer system which is not causally invertible, allowing a wider range of more complex transfer systems to be controlled. A robustness analysis is given and experimental results presented.

[13] P.J. Gawthrop, D.J. Wagg, and S.A. Neild. Bond graph based control and substructuring. *Simulation Modelling Practice and Theory*, 17(1):211--227, January 2009. Available online 19 November 2007. [bib | DOI]

> 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.

[14] P.J. Gawthrop, B. Bhikkaji, and S.O.R. Moheimani. Physical-model-based control of a piezoelectric tube for nano-scale positioning applications. *Mechatronics*, 20(1):74 -- 84, February 2010. Available online 13 October 2009. [bib | DOI]

> Piezoelectric tubes exhibit a highly resonant mode of vibration which, if uncontrolled, limits the maximum scan rate in nano-scale positioning applications. Highly resonant systems with collocated sensor/actuator are often controlled using resonant shunt dampers. Unfortunately, in the configuration used here, this approach is not possible due the non-minimum phase property arising from the presence of a right-half plane zero. This problem is solved by: (i) interpreting the resonant shunt damper in the context of physical-model-based control (PMBC) and (ii) extending the PMBC approach to handle non-minimum phase systems. The resultant controller combines the physical insight of the resonant shunt damper with the ability to control the non-minimum phase piezoelectric tube. A digital implementation of the controller was experimentally evaluated and found to successfully eliminate the resonant mode of vibration during an accurate and fast scan using a piezoelectric tube actuator.
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> Keywords: Flexible structures

[15] P.J. Gawthrop and F. Rizwi. Coaxially coupled inverted pendula: Bond graph-based modelling, design and control. In Wolfgang Borutzky, editor, *Bond Graph Modelling of Engineering Systems*, pages 179--194. Springer New York, 2011. [bib | DOI]

> A bond graph method is used to examine qualitative aspects of a class of unstable under-actuated mechanical systems. It is shown that torque actuation leads to an unstabilisable system, whereas velocity actuation gives a controllable system which has, however, a right-half plane zero. The fundamental limitations theory of feedback control when a system has a right-half plane zero and a right-half plane pole is used to evaluate the desirable physical properties of coaxially coupled inverted pendula. An experimental system which approximates such a system is used to illustrate and validate the approach.

[16] Peter Gawthrop, S.A. Neild, and D.J. Wagg. Dynamically dual vibration absorbers: a bond graph approach to vibration control. *Systems Science and Control Engineering*, 3(1):113--128, 2015. [bib | DOI]

> This paper investigates the use of an actuator and sensor pair coupled via a control system to damp out oscillations in resonant mechanical systems. Specifically the designs emulate passive control strategies, resulting in controller dynamics that resemble a physical system. Here, the use of the novel dynamically dual approach is proposed to design the vibration absorbers to be implemented as the controller dynamics; this gives rise to the dynamically dual vibration absorber (DDVA). It is shown that the method is a natural generalisation of the classical single-degree of freedom massâspringâdamper vibration absorber and also of the popular acceleration feedback controller. This generalisation is applicable to the vibration control of arbitrarily complex resonant dynamical systems. It is further shown that the DDVA approach is analogous to the hybrid numerical-experimental testing technique known as substructuring. This analogy enables methods and results, such as robustness to sensor/actuator dynamics, to be applied to dynamically dual vibration absorbers. Illustrative experiments using both a hinged rigid beam and a flexible cantilever beam are presented.
