FEATURE FOCUS: Mechatronics

THE LANGUAGE OF INTERACTION

Long before "mechatronics" was coined, there were bond graphs. Today, they keep tabs on the energy in systems of every kind. **By Dean Karnopp and Donald Margolis**

FROM CARS TO WASHING machines, from mirrors for laser surgery to control surfaces for space shuttles, virtually every mechanical system is a candidate for electronic control. To perform correctly, these mechatronic systems all depend on the interaction of sensors, computers, and actuators.

Yet, taking complex dynamic systems all the way from concept to commercialization requires mathematical models. Such models can include those whose equations the modeler derives directly. They can also include equations the modeler develops with software that holds the mathematics in the background. Programs exist for fluid mechanics, heat transfer, and hydraulics, to name a few.

Mechatronic systems use sensors to convert mechanical measures into electrical signals. Sensors are dynamic, and sometimes must themselves be modeled. Computer algorithms issue commands to actuators based on sensor outputs. The actuators convert electrical inputs to mechanical motions.

To model a mechatronic system, all these subsystems must be connected. All nonlinearities typical of a specific energy domain must be accounted for. To do this, a language is needed to describe the different energy domains in communal terms. Using such a language, submodels can be connected in an overall model, which can then be simulated by computer.

Physical systems that interact all store, transport, or dissipate energy among subsystems. Bond graphs provide a concise pictorial representation of these interacting dynamic systems. Bond graphs account for all energy and, in so doing, provide the common link among various engineering systems. A "bond" represents the energy exchange among subsystems. Each bond carries power. The product of two variables, effort and flow, represents this power.

University of California, Davis, professors Dean Karnopp and Donald Margolis recently completed a book on mechatronics: **System Dynamics: Modeling and Simulation of Mechatronic Systems,** ***2000, John Wiley.***

These variables have familiar names for any specific energy domain (below). Only two other variables are needed to represent all energetic systems: the momentum variable, defined as the integral of the effort, and the displacement variable, defined as the integral of the flow.

With bond graphs, all subsystems can be represented with a mere nine elements (page 49, top). The physics of some elements require that the list expand to include multiport versions of energy dissipation, storage, and transfer (page 49, bottom).

Energy Domain	Effort,e	Flow,f	Momentum,p	Displacement,q
Mechanics (Translation)	Force [N]	Velocity [m/s]	Impulse [N.s]	Position [m]
Mechanics (Rotation)	Moment [N.m]	Ang. Vel. [rad/s]	Ang. Impulse [N.m.s]	Angle [rad]
Electrics	Voltage [V]	Current [A]	Flux Linkage [V.s]	Charge [C]
Hydraulics	Pressure [Pa]	Volume Flow [m^3/s]	Press. Impulse [Pa.s]	Volume [m^3]
Thermodynamics	Temperature [K]	Entropy Flow [W/K]	---	Entropy [J/K]
Magnetics	Magnetomotive Force, [A]	Flux Rate [Wb/s]	---	Flux [Wb]
Diffusion	Chemical Potential,[J/mole]	Molar Flow [mole/s]	---	Quantity [mole]
Chemical Reaction	Affinity [J/mole]	Reaction Rate [mole/s]	---	Advancement [mole]
Pseudo-Bond Graphs, Thermo-Fluid Systems	Temperature [deg C]	Energy Flow [W]	—	Energy [J]
	Pressure [Pa]	Mass Flow [kg/s]	—	Mass [kg]

Only four power and energy variables are needed to represent any system.

Element	Constitutive Relationship	Comments
R	$e = \Phi_R(f)$	Resistance, dissipates energy
C	$e = \Phi_C(q)$ $q = \int f\,dt$	Compliance, stores energy
I	$f = \Phi_I(p)$ $p = \int e\,dt$	Inertance, stores energy
S_E	$e = \Phi_e(\underline{x}, t)$ $\underline{x} \equiv$ system states	Effort source
S_f	$f = \Phi_f(\underline{x}, t)$ $\underline{x} \equiv$ system states	Flow source
MTF (m)	$e_1 = m e_2$ $f_2 = m f_1$	Transformer (used to cross energy domains)
MGY (r)	$e_1 = r f_2$ $e_2 = r f_1$	Gyrator (used to cross energy domains)
0	$e_2 = e_1$ $e_3 = e_1$ $f_1 = f_2 + f_3$	Junction elements
1	$f_2 = f_1$ $f_3 = f_1$ $e_1 = e_2 + e_3$	Junction elements

Nine basic elements are combined to create a model of a system.

When subsystems composed of sensors and actuators are connected, an overall system model evolves. This overall model represents the dynamics of the entire system. Actual inputs are exposed. That is, if a controller sets a voltage for an electrohydraulic actuator, that voltage appears as an input on the bond graph.

Perhaps the most important feature of bond graph models is their easy determination of causality. Consider, for example, two subsystems that exchange energy or power. Connected by a bond that has effort and flow as variables—whose product is instantaneous power—the model needs to know which variable is the input and which variable is the output. Although nature does not care about causality, computers do.

For computer algorithms to solve equations representing the physics of real systems, it is essential that proper input and output causality be maintained. Some perfectly reasonable physical models simply will not compute because of causal problems.

With bond graphs, causality is indicated by a perpendicular stroke at the end of a bond. Thus, assigning causality is a straightforward task. State variables and computational problems are known completely after assigning causality, before the modeler derives a single equation. This point proves incredibly useful for modeling mechatronic systems.

It turns out that computers can read bond graph descriptions and can automatically evaluate causality, derive equations, query users about specific nonlinearities and inputs, and simulate systems. Several programs, available commercially, do this. Other software packages place bond graph submodels behind device icons, so users build overall models merely by assembling icons.

The same array of elements can be used regardless of the kind of system being modeled. Linear and nonlinear elements are represented with the same symbols. Nonlinear kinematic motions can also be shown. Imagine a computer transforming bond graphs into equations to simulate the overall dynamics of a system.

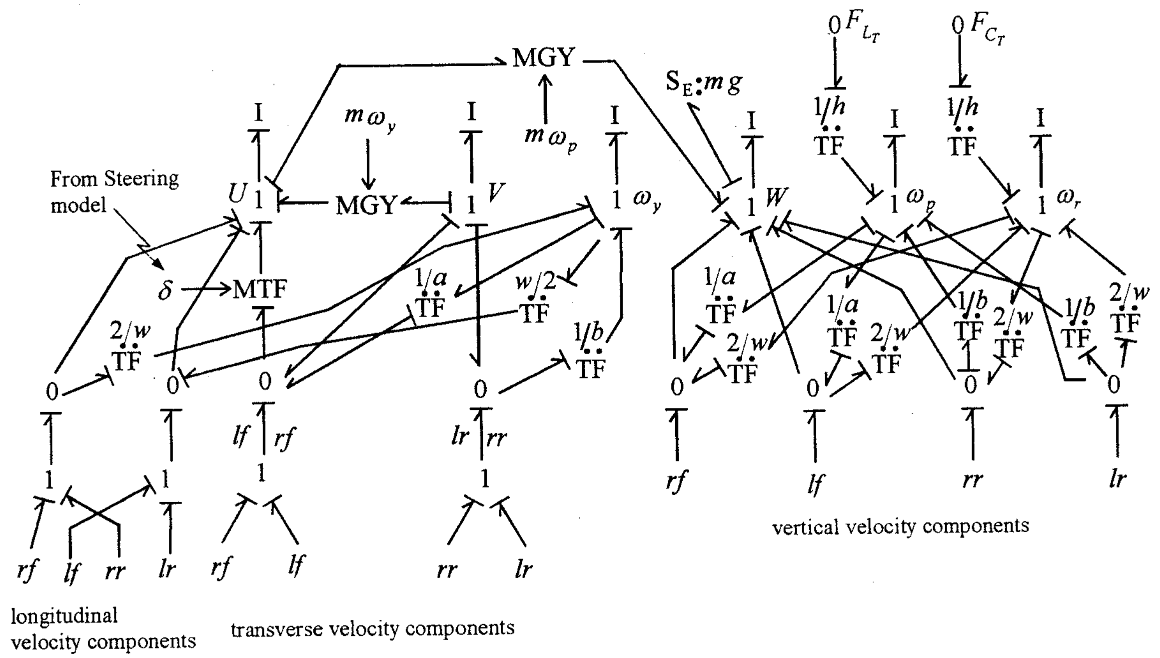
The two sample bond graphs that follow show a mechatronic system for conceptualizing the interaction of vehicle steering, braking, and suspension actuators for electronic control of automobiles. This model depicts an additive steering system in which a differential in the steering column, under computer control, adds to or subtracts from the driver's turn of the steering wheel without turning the steering wheel itself. Such a system, coupled with appropriate sensors, could improve vehicle safety.

The model also includes electric brakes at each wheel, comprising electric motors driving ball screws that move pads against discs. Suspension actuators at each corner of the vehicle are force actuators. The vehicle itself is modeled as a rigid body capable of motion in three dimensions. Angular motion for roll and pitch are assumed to be small.

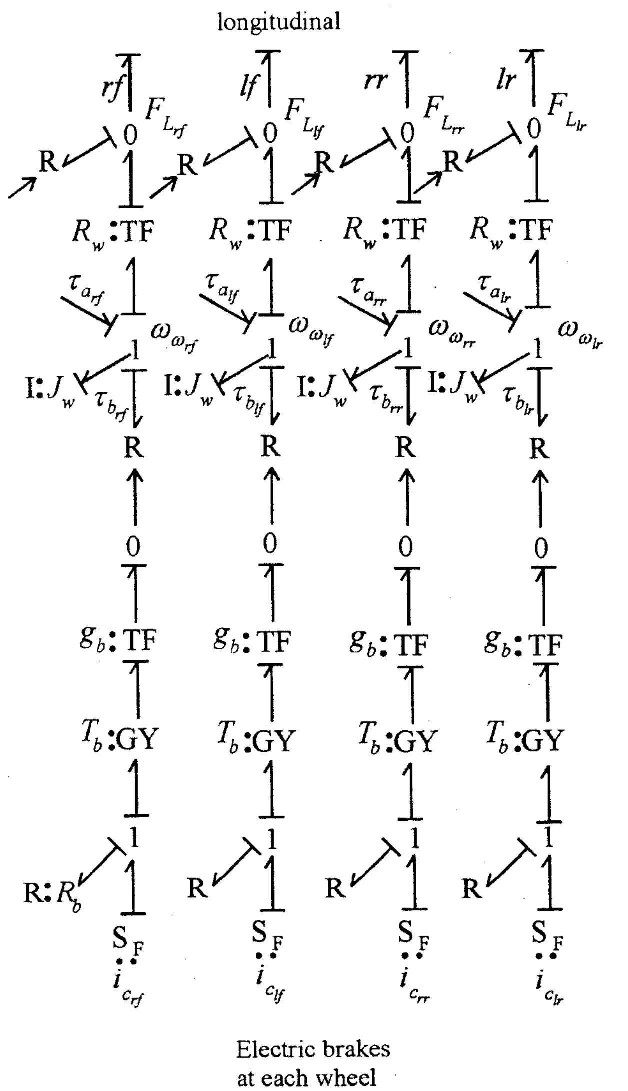
One sample bond graph of rigid body dynamics shows the generation of output velocities at all four corners in the longitudinal, lateral, and vertical directions (page 50, top). The other sample bond graph—a fragment, really—shows the electric motor brake actuators and the generation of longitudinal forces at the contact patches of the tires (page 50, left). This fragment attaches to the first bond graph at the location labeled "longitudinal velocity

Element	Constitutive Relationship
R (ports 1, 2, 3, …, n)	$e_1 = \Phi_{R_1}(f_1, f_2, \ldots f_n)$ ⋮ $e_n = \Phi_{R_n}(f_1, f_2, \ldots f_n)$
C (ports 1, 2, 3, …, n)	$e_1 = \Phi_{C_1}(q_1, q_2, \ldots q_n)$ ⋮ $e_n = \Phi_{C_n}(q_1, q_2, \ldots q_n)$
I (ports 1, 2, 3, …, n)	$f_1 = \Phi_{I_1}(p_1, p_2, \ldots p_n)$ ⋮ $f_n = \Phi_{I_n}(p_1, p_2, \ldots p_n)$
MTF (I: 1, 2, …, n; II: 1, 2, …, m; $\underline{M}$)	$\underline{f}_I = \underline{M}\,\underline{f}_{II}$ $\underline{e}_{II} = \underline{M}^t\,\underline{e}_I$
MGY (I: 1, 2, …, n; II: 1, 2, …, m; $\underline{R}$)	$\underline{e}_I = \underline{R}\,\underline{f}_{II}$ $\underline{e}_{II} = \underline{R}^t\,\underline{f}_I$

Multiport extensions of the basic elements handle complex subsystems.



This bond graph depicts the rigid body dynamics of an automobile. Electronic controls direct the vehicle's steering, braking, and suspension systems.



This bond graph fragment models tires and brake actuators.

components." Output velocities from the first bond graph are inputs to the second bond graph. Conversely, tire forces are outputs from the second bond graph and inputs to the first. Other fragments, not shown, represent the suspension components and actuators. Other fragments would show the generation of transverse tire forces. Taken together, these bond graphs create an overall mechatronic model of the vehicle, which includes sensors, actuators, and vehicle mechanics.

From their earliest beginnings at MIT in the 1950s, bond graphs dealt with topics of importance to mechatronics. They emphasized dynamic systems rather than steady state systems. Bond graphs had a natural connection with state space equations based on energy variables.

Although electronic devices did not dominate automatic control systems then as they do now, successful control system design depended upon accurate mathematical models of a plant, for example. For linear models, bond graphs provided transfer function representations. More interesting still, these representations handled nonlinear systems almost as easily as they did linear systems through the use of analog and, later, digital computer simulation.

Bond graphs dealt with mixed energy domain systems as well. Analogies among various systems, such as equivalent electrical circuits for mechanical vibratory systems, were never complete because each field had unique features. Bond graphs use analogous power and energy variables in all energy domains, but allow the special features of the separate fields to be represented.

The word "mechatronic" implies a combination of mechanical and electronic (and electrical) elements, but many systems—hydraulic, pneumatic, magnetic, thermodynamic, acoustic, chemical—can be modeled in the uniform notation of bond graphs.

The Web site, www.ece.arizona.edu/~cellier/bg_papers.html, has many references to bond graph modeling. ■