Modeling and Simulation Semantics for Building Large-Scale Multi-Domain Embedded Systems

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Abstract

This paper discusses a set of semantic constraints that have to be applied for multi-domain modeling of complex, embedded systems. In particular, using the Hybrid Bond Graph (HBG) modeling language, we analyze issues that deal with consistent causality assignments across model reconfigurations using hybrid switching junctions, and the complementarity of the electrical and mechanical domains by imposing additional constraints in the modeling environment. A case study of a Reverse Osmosis system developed at NASA JSC illustrates the effectiveness of our approach.

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I. Introduction

Today's embedded and cyber physical systems incorporate complex hybrid behaviors. Hybrid models of these systems capture the continuous behavior of physical processes interspersed with discrete changes that may be attributed to controller actions and abstractions of complex nonlinear behaviors. It is important to model these behaviors accurately to support design, control, monitoring, and safety analysis.

Bond graphs are an intuitive graphical energy-based multi-domain paradigm for modeling physical processes for modeling large complex systems. However, the core bond graph paradigm does not support the modeling of hybrid behaviors. In our research [6], we have developed hybrid bond graphs (HBGs) to support hybrid system modeling by incorporating switched junctions that accommodate dynamic mode switching and model updates during simulation. We have successfully applied this approach to develop modeling, simulation and analysis environments [7] [9]. However, to generate correct models, the modeler has to consider a number of modeling constraints, which were not explicitly defined in the earlier HBG paradigms, to ensure that a correct model is constructed. In this paper, we detail these additional modeling constraints. The constraints specifically relate to (1) ensuring causally feasible models in all modes of operation, and (2) taking into account domain differences between the electrical, hydraulic, and mechanical physical domains.

II. Hybrid Bond Graph Review

Bond graphs [5], and hybrid bond graph extensions, provide a modeling paradigm for modeling and simulating of hybrid cyber-physical systems. Bond Graphs model power and energy flow through multi-domain systems using generalized effort and flow variables to support domain independence. Generic Bond graph elements include: dissipaters (resistors, R), storage elements (capacitors, C, and inertias, I), transformers (transformers, TF, and gyrators, GY), sources and sinks (source of effort, Se, and source of flow, Sf), and idealized distribution elements(1-junctions, 1, and 0-junctions) [5]. Each element has its set of constitutive equations governing its behavior, and are connected to the rest of the system using bonds. Each bond is associated with an effort and a flow variable (effort $\times$ flow = power). Causality assignment in the graph identifies the dependent and independent variables for individual elements, and facilitates simulation of system behavior.

Hybrid Modeling Schemes

A number of researchers have proposed schemes for modeling hybrid behavior with bond graphs. [4] and [8] proposed a new switch element that exhibited different behavior depending on the junction it is connected to. A switch connected to a 1-junction forces zero effort when on, and zero flow when off. Similarly, when connected to a 0-junction the switch forces zero flow when on and zero effort when off. The behavior generated by this scheme is equivalent to HBGs [6] but it is not as intuitive because the switch element changes behavior depending on the junction it is connected to. [3] suggested similar functionality but did not use the switched bond graph element. [2] proposed a method of switching using a modulated transformer and a constant resistor. The transformer parameter changes between 1 and 0 to represent the switch being on or off and the connected resistor has a constant value representing the on conductance or the off resistance depending on the causality assigned to the resistor. The

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TABLE I: Primitive bond graph elements

Element Name	Causality	Equations
Source of effort, (Se)	Se:$u(t)$	$e = u(t)$
Source of flow, (Sf)	Sf:$u(t)$	$f = u(t)$
Resistor, (R)	R:R R:R	$f = e/R$ $e = Rf$
Inertia, (I)	I:I	$f = \frac{1}{I}\int edt$
Capacitor, (C)	C:C	$e = \frac{1}{C}\int fdt$
Transformer, (TF)	1 TF:n 2 1 TF:n 2	$e_1 = n * e_2$ $f_2 = n * f_1$ $e_2 = e_1/n$ $f_1 = f_2/n$
Gyrator, (GY)	1 GY:r 2 1 GY:r 2	$e_1 = r * f_2$ $e_2 = r * f_1$ $f_2 = e_1/r$ $f_1 = e_2/r$
1-junction, (1)	1 1 2 3	$f_1 = f_2 = f_3$ $e_1 = e_2 + e_3$
0-junction, (0)	1 0 2 3	$e_1 = e_2 = e_3$ $f_1 = f_2 + f_3$

method also proposed a simpler approach where only a resistance with a variable parameter value was used as the switch. Both of these approaches have the advantage of modeling non-ideal switches and the causality assignment is the same for both states of the switch. However, this method does not allow models where the switch physically disconnects, and, therefore, no power flows through the switch.

[10] introduced the concept of switched power junctions (SPJ). The SPJ generalized the traditional bond graph junction causality laws to allow for multiple determining bonds for each junction, but only one of the determining bonds could be active (transferring power) at a time. SPJs preserve causality for all switch modes, but the bond graph models can quickly become complicated with the extra bonds increasing the complexity of the system structure in each operating mode.

Hybrid Bond Graphs

Hybrid Bond Graphs, introduced in [6], proposed the idea of idealized switches in the form of switching junctions that can be turned on and off to represent different system modes. When on, a switched junction behaves as a normal 1- or 0-junction. When off, a switched 1-junction forces zero flow on its connected bonds, and an off 0-junction forces zero effort on its connected bonds.

Two different ways have been proposed to implement hybrid junctions. The original definition, shown in Fig 1 replaces the "off" state of the 1- (0-)junction with a corresponding zero flow (effort) source [6]. Later, [7] and [9], implemented the "off" state of a junction by removing the bonds incident on the junction (Fig 2) assuming that these bonds transferred no power, therefore, they had no effect on system behavior and could be safely removed. However, this is not always true, as demonstrated in Fig 3. The circuit behavior is relatively simple. The switch starts closed and the capacitor charges from an uncharged state. At some point the switch is opened, which, in the ideal case, blocks the current flow through the system and causes the capacitor to maintain its charge. The unsimplified bond graph for the circuit is also shown in Fig 3. When the hybrid behavior is implemented by removing the bonds connected to the hybrid junction, the remaining bonds on the adjacent 1-junction allows the capacitor, C to discharge through the resistance, R. This is counter to the behavior expected from the circuit diagram. Therefore, the hybrid junction implementation shown in Fig 1 is not valid in general.

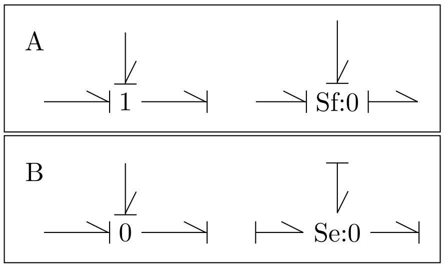

Fig. 1. Method of Implementing Hybrid Bond Graphs by Forcing Zero Effort/Flow in the Off Hybrid Junction

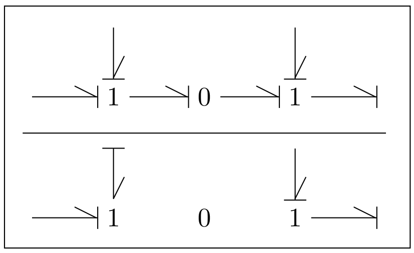

Fig. 2. Method of Implementing Hybrid Bond Graphs by Removing Bonds Attached to the Off Hybrid Junction

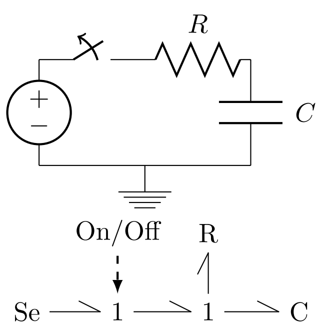

Fig. 3. Circuit Example and Unsimplified Bond Graph

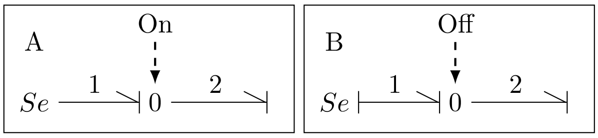

Fig. 4. Part A: Bond Graph with 0-Junction On and Part B: Causal Conflict on Bond 1

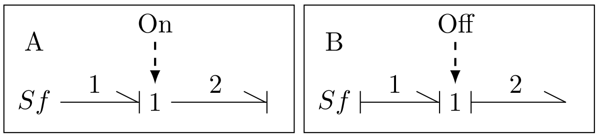

Fig. 5. Part A: Bond Graph with 1-Junction On and Part B: Causal Conflict on Bond 1

III. Hybrid-Bond Graph Modeling Constraints

When creating HBG models a set of constraints have to be applied to ensure the generated models are correct by: (1) avoiding structures that produce causality conflicts, and (2) being cognizant of the duality between mechanical versus electrical and fluid domains when constructing the hybrid junction structures for a system.

Modeling Constraint 1: Prohibited Structures

Assuming our models represent physical processes, the causality of the elements should not be violated in any mode of operation. Situations that violate causality may appear legitimate, but when the junction turns off there can be no causality assigned to the system. Such situations occur when a Se (Sf) element is directly connected to switching a 0-junction (1-junction). Turning the junction off creates a causality violation because there are two active sources of the same type incident on the 0- or 1-junction, respectively. This is illustrated in Figs. 4 and 5, respectively.

A related situation occurs when a capacitor (inertia) in integral causality is connected to a hybrid 0-junction (1-junction). When on, the capacitor (inertia) determines the junction effort (flow) value. When the junction turns off, keeping the capacitor (inertia) element in integral causality, (i.e., the determiner of the state variable effort (flow) value) creates a causality conflict with the zero effort (zero flow) source introduced to model the "off" state of the junction. Since a source element has fixed causality, the capacitor (inertia) is changed to derivative causality to accommodate the conflict. This implies that the derivative of effort (flow) immediately goes to zero, causing an instant discharge of all of its stored energy. This may not represent the correct behavior of the capacitor, i.e., it should retain its charge when it is isolated. (A similar statement can be made about the flux value on the inductor).

The situations described above are caused by the forced change in the determining bond (i.e., the bond that determines the effort value of a 0-junction and the flow value of a 1-junction) when the junction switches from on to off. In the examples in Figs. 4 and 5, causally correct structures across switching states can be retained by pairing a source of effort with a hybrid 1-junction, and a source of flow with a hybrid 0-junction. We introduce this as a formal constraint into our embedded systems modeling paradigm.

Modeling Constraint 2: Handling Complimentary Domains

Bond graph represent power flow through a system in a domain independent way. However, with HBGs, additional constraints may have to be added to created correct models.

The basis for this domain duality is based on fundamental differences between the physical domains. Each domain has a variable that represents a relative quantity, and a variable that represents an absolute quantity. That is, in the electrical domain (the hydraulic domain has similar behavior) the voltage (effort) at a point can only be measured relative to another point, while the current (flow) can be measured at any point in the system and does not need a reference. The opposite is true for the mechanical domains, where the velocity (flow) can only be measured relative to another point, while measuring the force (effort) does not require a reference point. The relative and absolute variables in the electrical and mechanical domains are represented by complementary bond graph variables. This difference translates to how configuration switching is modeled in each domain. Regardless of domain, each switch operates at a specific point in a system, not across or in reference to another point. This means that an electrical switching junction turned off will result in zero current (flow) through that node, while a mechanical switch turned off will result is zero force or torque (effort) being transmitted between objects. Given that switches in the different domains have dual semantics, they need to be represented as different junctions. In the electrical and hydraulic domains, the primary switches are modeled as 1-junctions to impose the constraint that flow (current and mass flow) is zero when the switch is off. In the mechanical domain, the primary switches are modeled as 0-junctions, because the effort (force and torque) are not transferred across the open switch. The other junction can be included in bond graph models as a secondary switch, but the physical implementation of the secondary switch is more complicated than the primary switch. This will be illustrated in the following section.

Similar logic can be used to determine the behavior for the reference point in each domain. The reference point in each domain provides the base reference for measuring the relative variables in that domain. The reference point is used in relation to other points in the model, therefore, the reference point forces a zero value on the relative quantity in that domain, which is the opposite quantity affected by a switch. For example, in the electrical domain an ideal ground forces zero voltage (effort) and supports infinite current (flow), and in the rotational domain an ideal fixed point forces zero velocity (flow) and supports infinite force (effort). (See Table II.)

TABLE II: Switches and their Reference Points across Domains

Domain	Primary Switch Forces Zero	Implemented As	Fixed Forces Zero
Electrical	Current	1-Junction	Voltage
Mechanical Translation	Force	0-Junction	Velocity
Mechanical Rotation	Torque	0-Junction	Angular Velocity
Hydraulic	Mass Flow	1-Junction	Pressure

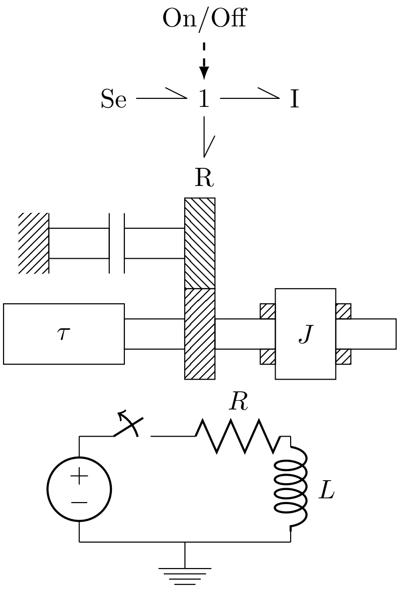

Fig. 6. Domain Duality Example 1

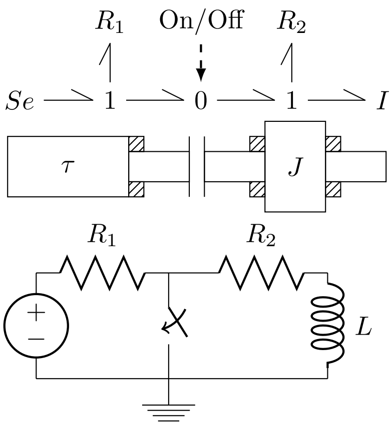

Fig. 7. Domain Duality Example 2

Complimentary Domains Example

To understand how the domain duality affects bond graph design, it helps to take a reverse modeling approach where the bond graph is the starting point instead of the end point. Figs 6 and 7 show an example of a simple bond graph implemented in two different domains.

In Fig 6 the hybrid 1-junction starts on, the flow in the system is dictated by the inertia element, and the sum of the efforts on each element sum to 0:

$$p = f * I = \int e dt \tag{1}$$

$$e_I = e_{Se} - e_R. \tag{2}$$

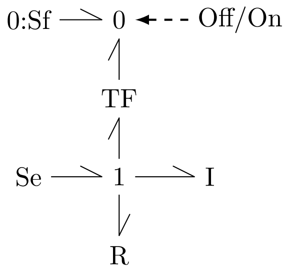

Fig. 8. Bond Graph of Rotational System in Fig 6

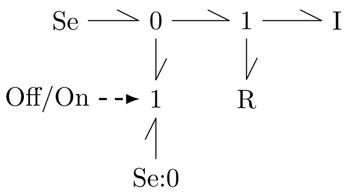

Fig. 9. Bond Graph Version of Electrical System in Fig 7

The variable p represents the momentum in the system and describes the system's state. At some point the 1-junction turns off, which will force the flow in the system to zero and will cause the inertia element to discharge instantly (that is, the momentum, p, in the system immediately drops to 0). The effort values also no longer need to sum to 0 because there is no more power flowing to each element:

$$p = f * I = \int e dt = 0. \tag{3}$$

It is easy to see how the electrical circuit is an implementation of the bond graph. There is only a single flow path through the bond graph, and that is reflected in a single current through the electrical system. However, the corresponding mechanical rotation implementation is difficult to construct due to the switched 1-junction in the bond graph. A hybrid 1-junction is not easy to represent in the mechanical rotational domain because, in the rotational domain, only a fixed reference point can force the zero flow (velocity) required by the hybrid 1-junction. Implementing the hybrid 1-junction requires that the clutch be connected to a fixed point through a set of gears. The clutch operates opposite the switch in the bond graph so that when the hybrid junction is on (behaving as a normal junction) the clutch is open (off) to let the shaft spin freely. When the hybrid junction turns off to force zero flow, the clutch closes (turns on) so that the zero velocity forced by the fixed point transfers to the load. The mechanical rotation implementation in Fig 6 is better represented by the bond graph in Fig. 8, where the hybrid 1-junction is replaced by a hybrid 0-junction, a transformer, and a source of flow representing the fixed point.

The situation is similar for the bond graph referenced in Fig. 7. The hybrid 0-junction starts on, which forces a single effort across both sides of the clutch, and the velocities on both sides of the clutch must sum to 0 (since there are only two bonds the velocities are going to be equal in magnitude but opposite in direction): $e_1 = e_2$ and $v_1 = -v_2$; where e_1 and v_1 are associated with the bond to the left of the 0-junction and e_2 and v_2 are associated with the bond on the right. At some point the hybrid junction turns off, which means the 0-junction now forces zero effort on its bonds: $e_1 = e_2 = 0$. The mechanical rotation implementation of the bond graph is simple, because the open clutch forces zero torque (effort) across it when open as required by the hybrid 0-junction. The electrical implementation is complex because it requires positioning the switch such that it creates a short to ground; which is the only way to force zero voltage (effort) as required by the off 0-junction. The electrical circuit in Fig 7 is better represented by the bond graph in Fig. 9. In this case the hybrid 0-junction is replaced by a regular 0-junction, a hybrid 1-junction, and a source of effort representing ground.

The extra structures needed to implement the secondary switch in each domain are actually the primary switch, a fixed point, and, potentially, extra elements to force the desired behavior. Using the secondary switching junction in each domain is possible, but it is impractical because the underlying physical structure of the system will simply use the primary switching junction.

IV. Case Study

As a case study to demonstrate the effectiveness of the definition of switching junctions and the role of the two constraints in the modeling task, we consider the Reverse Osmosis (RO) system, previously modeled in [1] and [9]. Both presentations of the RO system do not follow the definition of hybrid junctions, and instead implement hybrid behavior by assuming the bonds connecting an off junction are removed from the system.

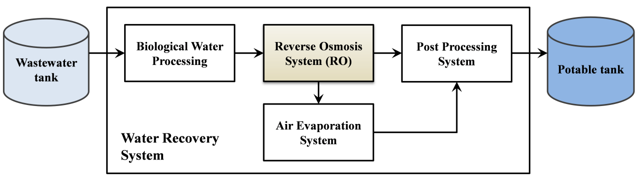

Fig. 10. NASA Water Recovery System.

Reverse Osmosis Overview

The RO system is part of the Advanced Water Recovery System (AWRS) (Fig 10), which is a subsystem of the NASA Advanced Life Support System (ALS). The ALS was designed as a way to support life for extended duration space missions by reclaiming waste water. The RO subsystem uses a membrane to remove inorganic matter and particles from water (Fig 11). The different modes of operation are controlled with a three-way valve, where each position of the valve specifies a different mode of operation. During the first two modes of operation, identified as M1 and M2, clean water leaves the system through the membrane, but dirty water, brine, is recirculated in a feedback loop to be filtered again. As a result of the feedback, the concentration of impurities in the water increases with time until it must be purged from the system, during mode P, to be processed by a different subsystem.

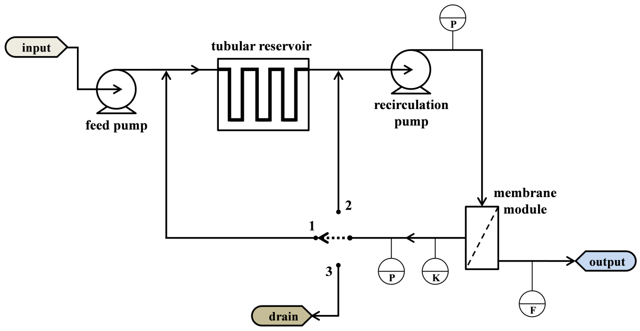

Fig. 11. RO Subsystem Schematic

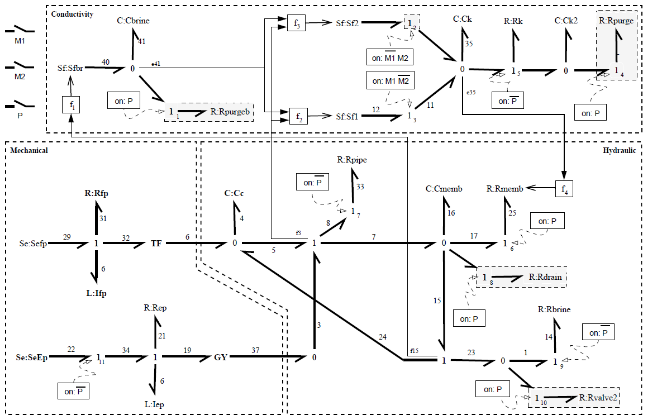

Fig. 12. RO System Bond Graph Version 1

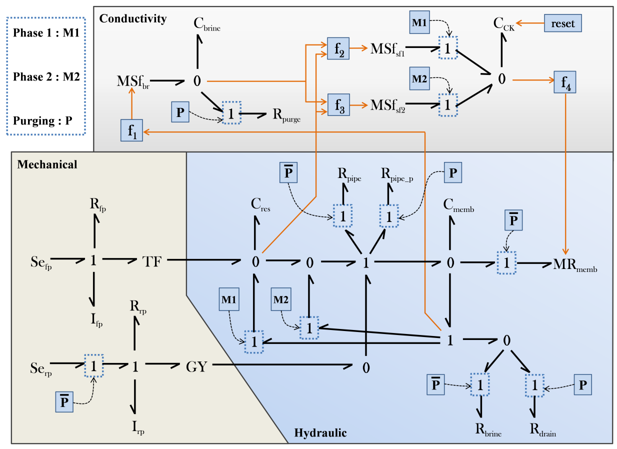

Fig. 13. RO System Bond Graph Version 2

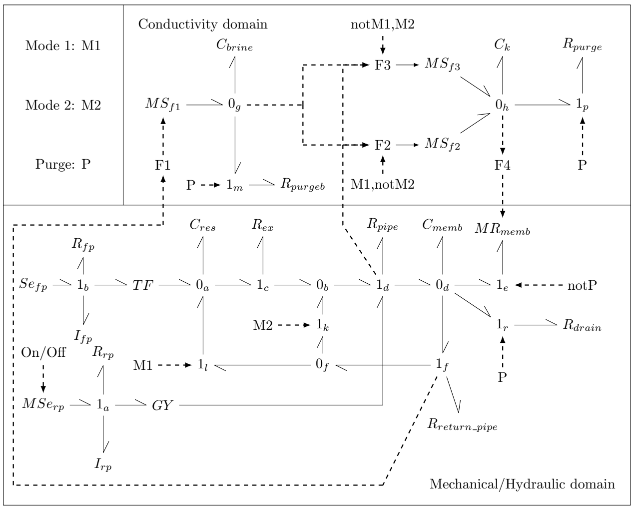

Fig. 14. Corrected Version of the RO System

Design Problems

The RO system has been modeled before, and the implementation from [1] is shown in Fig. 12 and the implementation from [9] is shown in Fig. 13. The hybrid junction implementations in these examples are based on the method presented in Fig. 2, where the only bonds removed from the system are the bonds directly connected to the hybrid junction. In both models, there are several places where multiple 1-junctions are connected together and one of the junctions is a hybrid junction. In Fig. 12 junction 7 (connected to *Rpipe* at the top of the mechanical domain) is a hybrid 1-junction connected through bond 8 to another 1-junction. The other situation in that figure is junction 11 (connected to source of effort *SeFp*), where a hybrid 1-junction is connected through bond 34 to a non-hybrid 1-junction. Fig. 13 has three situations where a non-hybrid 1-junction is connected to at least one hybrid 1-junction. The first case is the same as junction 11 in Fig. 12. The other two cases have a non-hybrid 1-junction connected to two hybrid 1-junctions, and the hybrid junctions are configured so that only one of the hybrid junctions is on at a time. The first instance is the two 1-junctions connected to the resistors R_{pipe} and R_{pipe_p}. The second instance is the 1-junction below the C_{memb} component that is connected to the two hybrid 1-junctions that switch on M1 and M2.

In both models, the intended behavior of these multiple junction structures is that there will be flow through the non-hybrid 1-junction when the connected hybrid junctions are off. However, when the proper definition of hybrid junctions is applied to these structures, the off 1-junction will stop the flow of fluid through the connected non-hybrid 1-junctions. This effectively makes the system inoperable as there will never be flow through the non-hybrid 1-junctions.

Another problem with Fig. 13 is that there are two 0-junctions next to each other near the middle of the figure (one 0-junction is connected to the capacitor C_{res}). The second 0-junction is supposed to represent the fluid path for mode M2 that avoids the reservoir, C_{res}, and forces fluid more quickly through the membrane. However, because the two 0-junctions function as a single junction, the fluid path for mode M2 is the same as for mode M1.

A final problem with both models is in the conductivity domain. There are two modulated flow sources, $Sf1$ and $Sf2$ that are connected to hybrid 1-junctions. When the hybrid junctions turn off there will be a causality conflict on the bond connecting the flow source and the junction because both will be trying to force a different value for the flow on that bond.

The simulation results for Fig. 13 are presented in Figs. 15 and 16. These results conflict with the results presented in [9] because they were generated using different definitions for the hybrid junctions. The results presented in [9] were created by removing the bonds connected to an off junction, while the results presented here were generated by forcing zero flow on the off hybrid 1-junctions. In Fig. 16 the system never transitions out of the purge mode because there is a check in the system that enables that transition based on the amount of brine in the system. As seen in Fig 15 the brine concentration is static, so the system is never able to complete the check, and, therefore, the system will stay in the purge mode indefinitely. The transitions out of modes M1 and M2 are strictly based on time, and are, therefore, not affected by the behavior of the system.

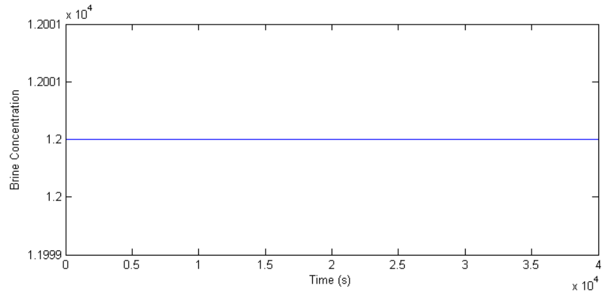

Fig. 15. Brine Concentration for the RO System Presented in Fig 13

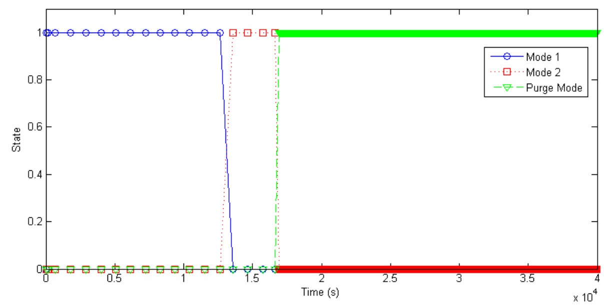

Fig. 16. Mode Transitions for the RO System Presented in Fig 13

Corrected Reverse Osmosis Model

To overcome the problems discussed above, a corrected bond graph of the RO system is shown in Fig. 14.

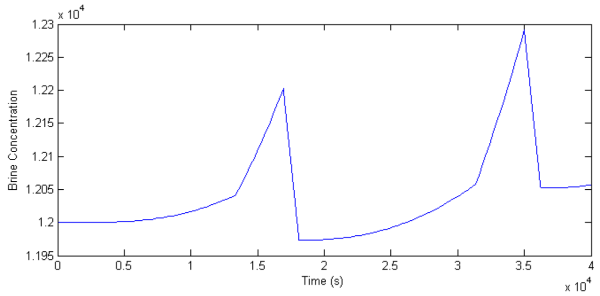

Fig. 17. Brine Concentration for the Corrected RO System

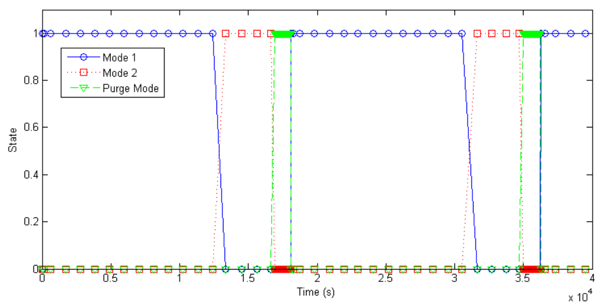

Fig. 18. Mode Transitions for the Corrected RO System

The hybrid 1-junctions at the top of the hydraulic domain have been removed and replaced with a single resistor element. This better models the fluid flow as it must pass through the pipe represented by junction 1_d in all modes. There is a 0-junction (junction 0_f) separating the M1 and M2 triggered 1-junctions. This 0-junction functions as a flow dividing junction and allows the hybrid 1-junctions to be turned on and off independently. In purge mode both junctions are off, which will force zero flow through junction 1_f, effectively turning it off even though it is not explicitly declared as a hybrid junction. The recirculation pump, MSe_{rp}, is now a modulated source of effort that replaces the hybrid 1-junction. Also, there is a new 1-junction (junction 1_c) with a connected resistor that separates the two series 0-junctions. This 1-junction allows there to be two different fluid flows for modes M1 and M2. Finally, the hybrid 1-junctions connected to the sources of flow in the conductivity domain have been removed and the hybrid functionality moved into the functions that define the values for the modulated sources of flow. The updated simulation results are presented in Figs. 17 and 18.

V. Conclusion

Hybrid bond graphs are an excellent cross domain method of representing the behavior of hybrid systems that capture the energy domain constraints and configuration switching constraints imposed on physical processes to ensure that models remain consistent before and after mode changes. The semantics of hybrid bond graphs produce valid behavior across multiple physical domains, provided the proper definition of a hybrid junction is followed, and the associated constraints are not violated. We have shown that only one type of primary switched junction makes sense physically in each domain, and even though the complementary junction can be used in each domain the physical system is better represented by using the ideal junction plus a few added elements. When the semantic constraints are applied, the HBG modeling paradigm is able to accurately represent the behavior of hybrid systems.

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Author Biographies

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