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Hyper-Bonds – Applications and Challenges

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A new concept of mixing distributed real and virtual worlds through a unified human-machine interface will be introduced, some first realizations and a focus on resulting challenges of control-theory and modeling are presented.

Mixed Reality Interfaces

Research fields like *Mixed Reality*, *Ubiquitous Computing*, *Embedded Systems* and *Cybernetics* beside their special orientations, all deal with the problem how to connect real physical phenomena to virtual, computer internal control or simulation models. There are several well developed unified concepts to describe discrete and continuous physical processes (Petri-Nets, Bond-Graphs), however there is a gap between control theory and its application to general and easy to use human-machine interfaces. There are only few concepts to bridge the real and virtual world in a *unified way*. The introduction of *Hyper-Bonds*, first demonstrated for quasi-static discrete event applications of pneumatic and electrical phenomena (Bruns, 1999, 2001), fig. 1, opens up promising perspectives of further research to merge existing knowledge and tools from various other fields. Bond-Graph Theory is a powerful candidate because of its unified view on effort/flow driven systems of mechatronics (Paynter, 1961), now beeing integrated into various simulators as modeling language (see 20sim, van Amerogen, 2000, and Medelica). However, there is still a high demand for interactive on the fly real time modeling and for hybrid systems with analog/discrete and real/virtual interfaces (see control theoretical aspects at Mostermann, 1997 and Melchiorri, C., 2003, tangible media aspects at Ishii, 1997 and image-centered mixed reality work of Ohta & Tamura 1999).

No comparable approach is known to the author where it is possible to duplicate and continue the real to the virtual and vice versa on a high semantic level.

Motivation for Hyper-Bonds and Bond-Graphs

Driven by a need of simulation experts and pedagogues to closely bring together simulation and real world phenomena, we developed several solutions to support the modeling process in mechatronics by systems specifications through concrete demonstration of the desired dynamic behavior (programming robot and conveyor systems by hand gestures and object movements). In a further development, it was possible to connect a real model to its virtual representation by image-recognition of user actions in a work- and learning-space, enabling learners and system designers to easily switch between real concrete and abstract virtual representations of the same system. Meanwhile first prototypes have been evaluated in several European Engineering and Vocational Schools, confirming our approach. A next step was, to expand this interface to a bidirectional connection, providing the user with electrical and air-pressure connectors on a real modeling desk and correspondingly in a virtual modeling world enabling him/her to connect a real pressure tube/electric wire coming from a pressure/voltage source to the interface and continue this phenomenon on a signal level in virtuality to drive a virtual component. This same process can be reversed, extending virtual signals into real physical phenomena. Using the internet for a distribution of multi-user virtual worlds then opens up new ways of distributed real-virtual co-operation. First results of a running project were we offer remote mechatronics laboratory services for European schools can be seen at http://www.labfuture.net. A 24 h running remote laboratory can be visited at http://lab.artec.uni-bremen.de.

These projects developed and evaluated hyper-bonds for low speed and discrete event driven systems. The theory of *bond-graphs* has been useful for insight into the similarity of processes from different domains, but there was no need to go into detailed modeling of the interface itself. This changes however, if we turn to high speed and continuous processes, like driving a remote work-load wheel by a local

hand-wheel through an internet-connection or continuation of an analogue pressure-change from a real source via internet to a real target. A low cost solution and experiences with users for the former problem have been presented (Yoo & Bruns, 2004), fig. 2. Another scenario usable in remote maintenance, remote human-human or human-robot collaboration could be a pneumatic push through the internet, fig 3. These applications require a sound theoretical background to handle real-time problems namely the stability and quality of control of dynamic systems.
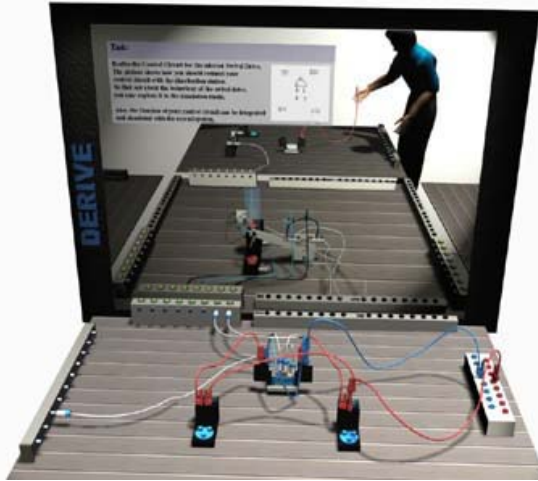

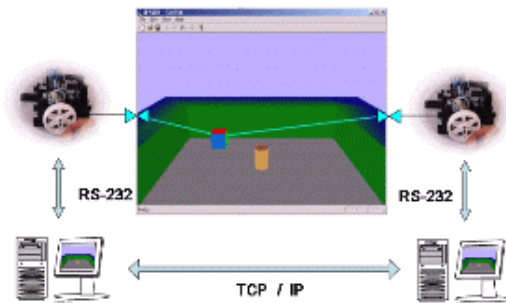
Fig. 1: Connecting real and virtual worlds
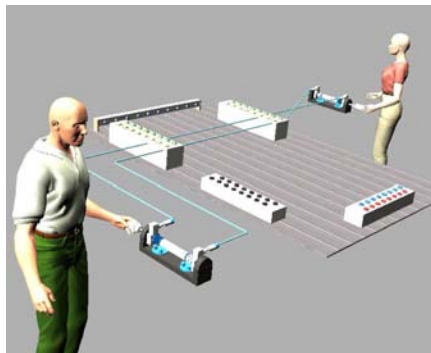

Fig. 2: Distributed Collaboration

Fig. 3: Pneumatic pushing via hyper-bonds

We imagine as a far reaching perspective the ultimate hyper-bond as an extension of the famous *ultimate display* envisioned by E Sutherland (1965), who thought about a display room, where "a bullet displayed in such a room would be fatal". From a control perspective we are not only interested in projected chairs to sit on or bullets not being hit by, but in a bi-directional action, crossing the boarder between the real and the virtual. The real pendulum coming out of a "magic" hyper-bond wall as an extension of the virtual pendulum having the same, translated and generated characteristics as the virtual pendulum, experiencing some changes in reality and then, swinging back, at the entrance into the hyper-bond wall, would again be converted into its virtual continuation. This scenario requires some second thoughts, but I am rather convinced that most engineers find many useful and joyful applications of this rather utopian scenario. However, considered from a cybernetic point of view, this poses a major theoretical and practical challenge.

We demonstrate how modeling of the complete real-virtual-real hyper-bond system with a simulator supporting bond-graphs (20sim), can give some insight into problems, possibilities and limitations.

Yoo (2004) has shown, that having some knowledge about one part of a mechatronic effort/flow network, this part can be replaced by a simple equivalent network of resistor, inductor and capacity, implemented as a real interface, thus connecting a known virtual network to an unknown real mechatronic network. This certainly is a most useful approach to connect virtuality with reality, except that necessary interface components for a full R-I-C network, are modulated capacities, which are not yet available to build a real universal hyper-bond. Furthermore, this concept might run into problems if both parts of the system are unknown. We therefore present a completely local implementation with the advantage of no necessary knowledge about the connected subsystems.

Theory of Hyper-Bonds

Theorem 1
Given an arbitrary system S described by a bond-graph BG with effort-flow elements: MSe (modulated source of effort), MSf (modulated source of flow), R (resistor), C (capacity), I (induction), 0 (constant effort node), 1 (constant flow node), energy and signal arcs, sensors of effort and flow, we can replace any energy connection by a subnet HB (Hyper-bond) conserving the overall behaviour and providing a mechanism to separate two physical subnets S1 and S2 connected via HB, a network of sensors and generators of effort and flow.

Theorem 2
Given a separation of two physical networks S1 and S2 connected via HB, an arbitrary implementation of S1 and S2 as real or virtual system is possible, restricted only by signal transmission time and sensor/generator characteristics.

The advantage of Theorem 1 is its local specification, which means that it is not necessary to know anything about the structure of systems S1 and S2. This locality is a valuable property for implementing distributed mixed reality. Theorem 2 provides the basis for the continuation of virtual simulation phenomena into reality and the continuation of physical phenomena into virtual models. Together they provide a powerful means to design and handle mechatronic systems.

As can be verified by simulation, two types of HB are possible

1. HBF senses the flow into or out of the connected subnets and generates two equal real or virtual efforts until both flows are equal,

2. HBE senses the effort and generates two equal but opposite flows

We demonstrate the approach in a stepwise transformation of a simple resistor network into two networks connected by a hyper-bond implementation using 20-sim as simulator.

Fig. 4 shows two connected resistors and two sources of effort in an iconic and a bond-graph representation. Applying a sine-wave generator on th left side and a cosine-wave generator on the right side, would result in a behavior given in fig 5 as the middle (green) line.
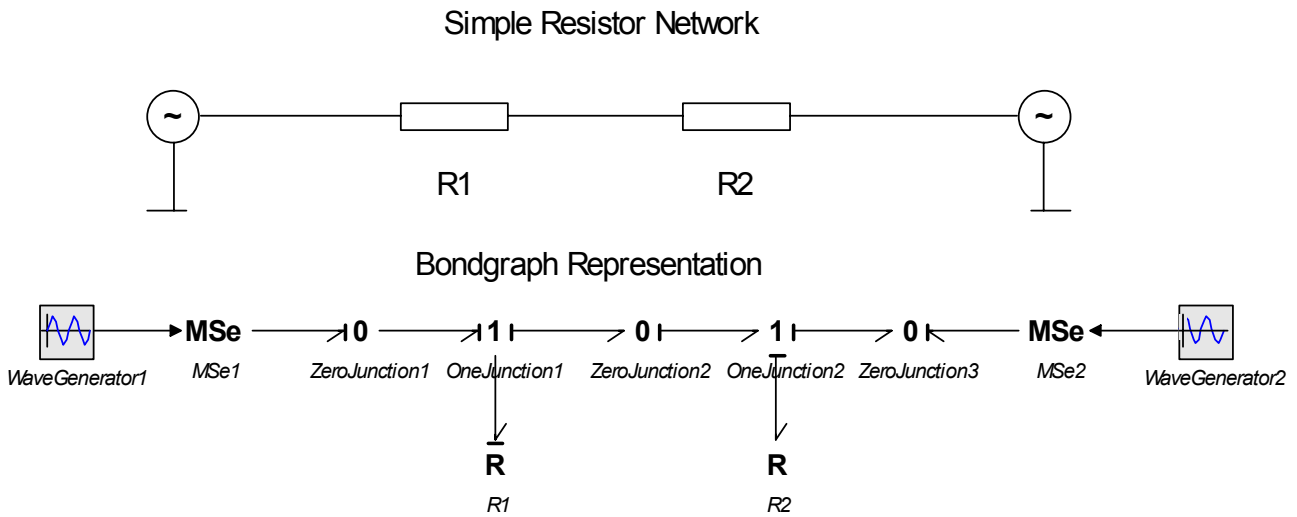
Fig. 4: Resistor Network in Bond-graph Representation
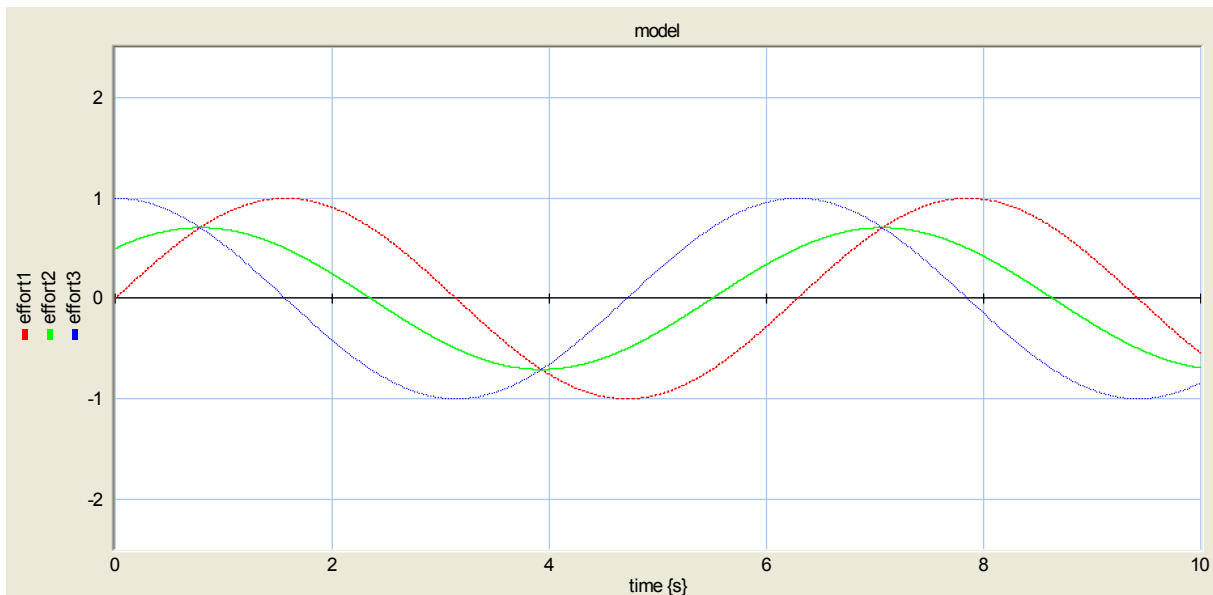
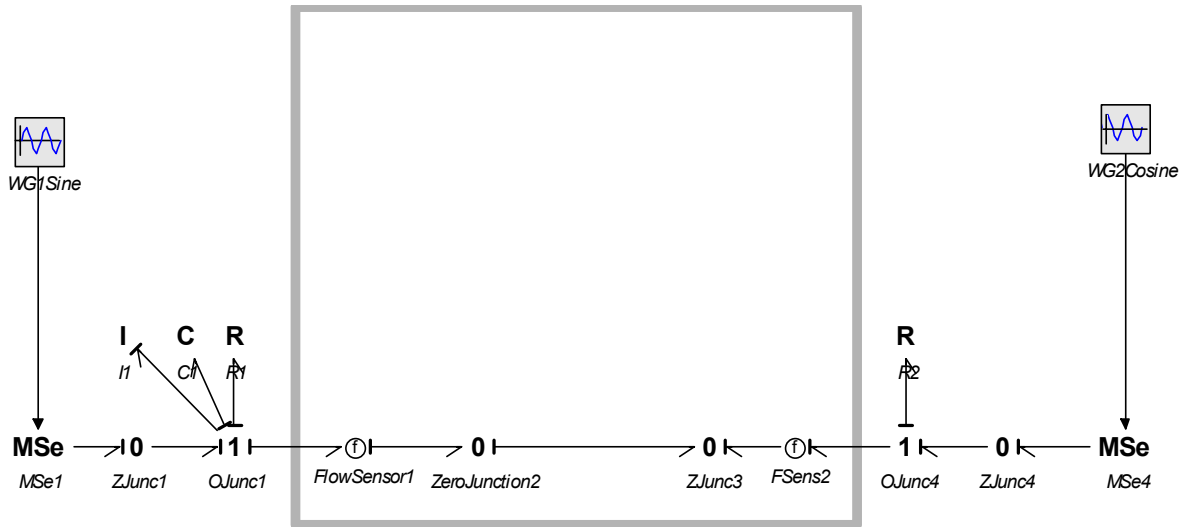Fig. 5: Result from 20-sim simulation
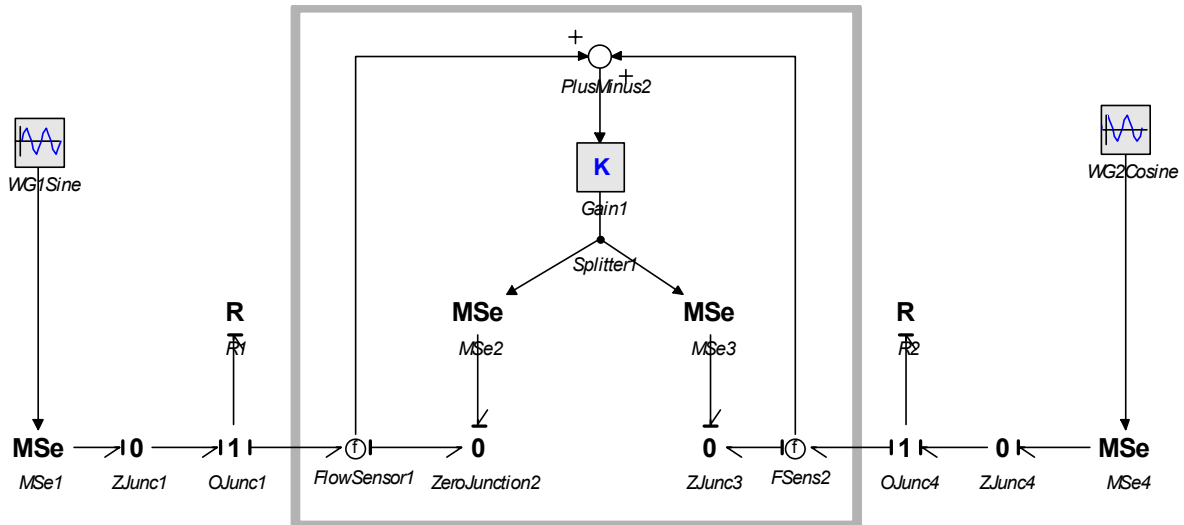
Fig. 6: Empty Concept of Hyper-bond

Fig. 7: Theoretical Hyper-bond

Fig. 6 presents the empty hyper-bond as a connection between two simple sub-networks. The behaviour of the original system, being cut into two parts, can be preserved by introducing a connecting network, which senses the flow at two boundary points. The difference of both efforts is used to generate two new sources of effort in a typical control-loop. It can be shown, that the result is indeed a preserved behaviour. However, this view is a theoretical one. Real implementations have to take into account the measurement and generation process. Introducing A/D-Converters at the measurement side and D/A-Converters at the generator site yields an implemented hyper-bond of fig 8. Depending on the D/A/D sampling rate, it can be seen in fig. 9, that for two 1 Hz sin-cosine effort-sources a 1 kHz sampling rate preserves the overall behaviour. A more complex network with inductivity I=0.1, capacity C=0.1 and resistor R=1.0 (fig. 10) would result in a more wavy behaviour, fig. 11, which again can be preserved by an implemented hyper-bond (fig. 12).
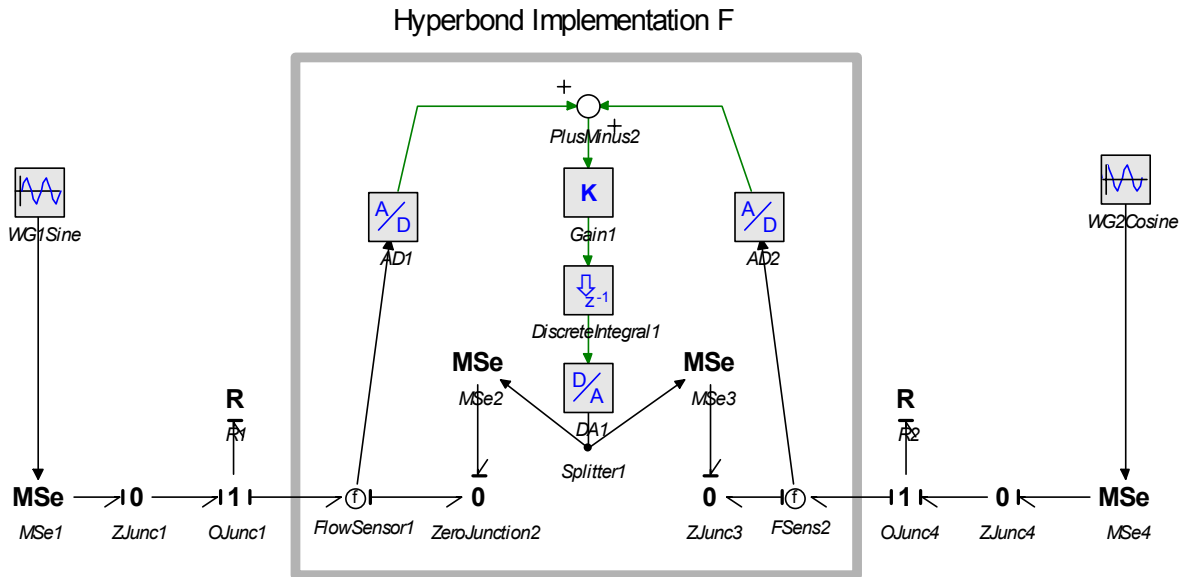
Hyperbond Implementation F
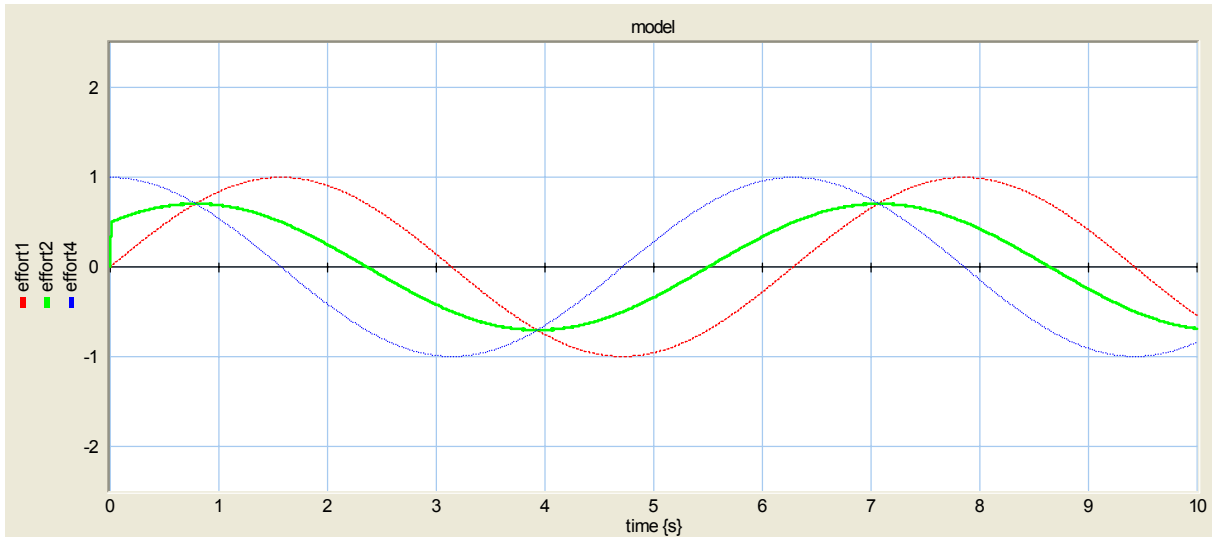

Fig. 8: Implementation of Hyper-bond F (sensing flow, generating effort)
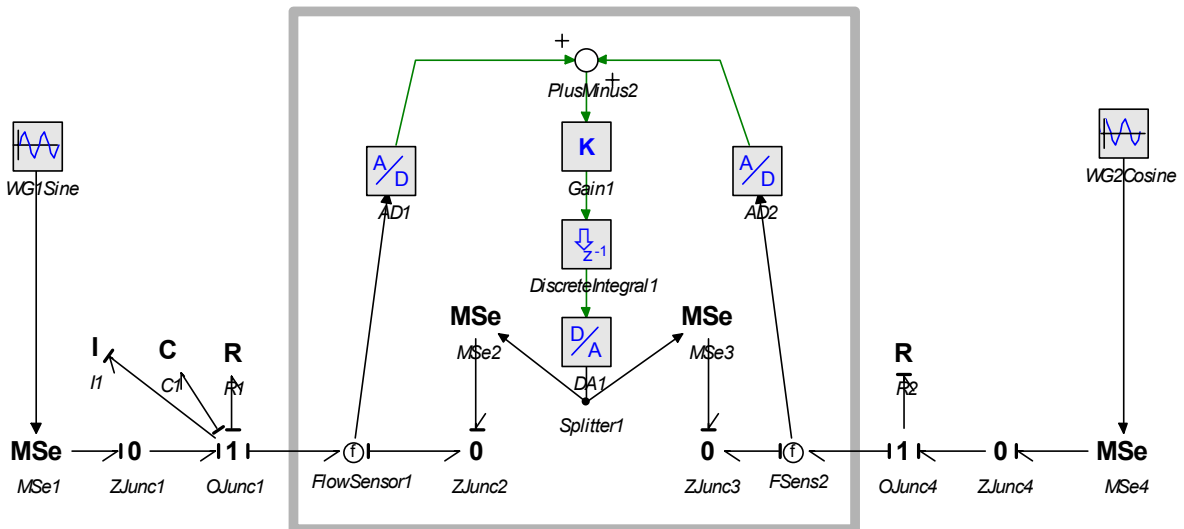

Fig. 9: Simulation of Hyper-bond Implementation

Fig. 10: Complex System with Inductivity I=0.1, Capacity C=0.1, Resistance R=1.0
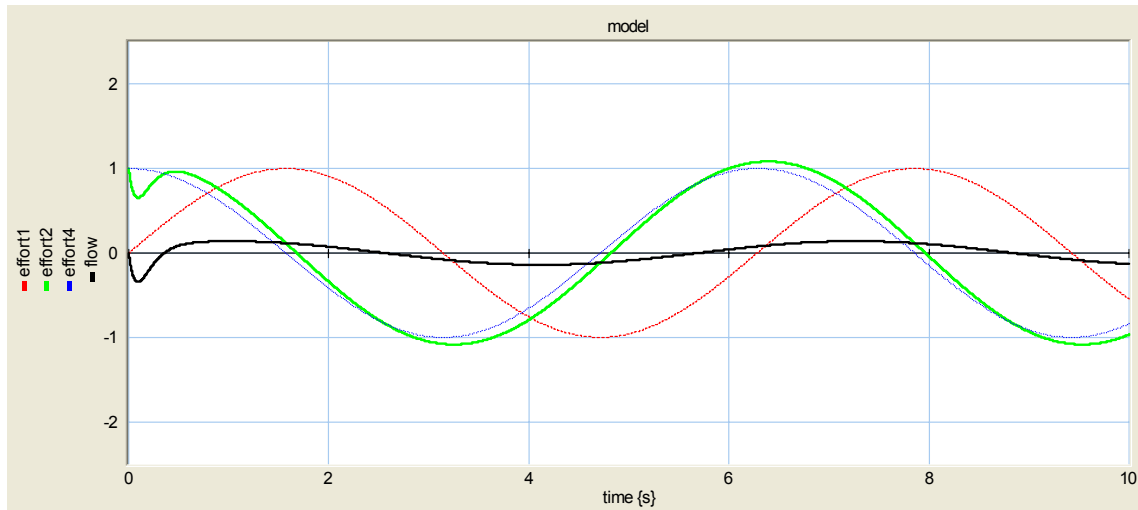

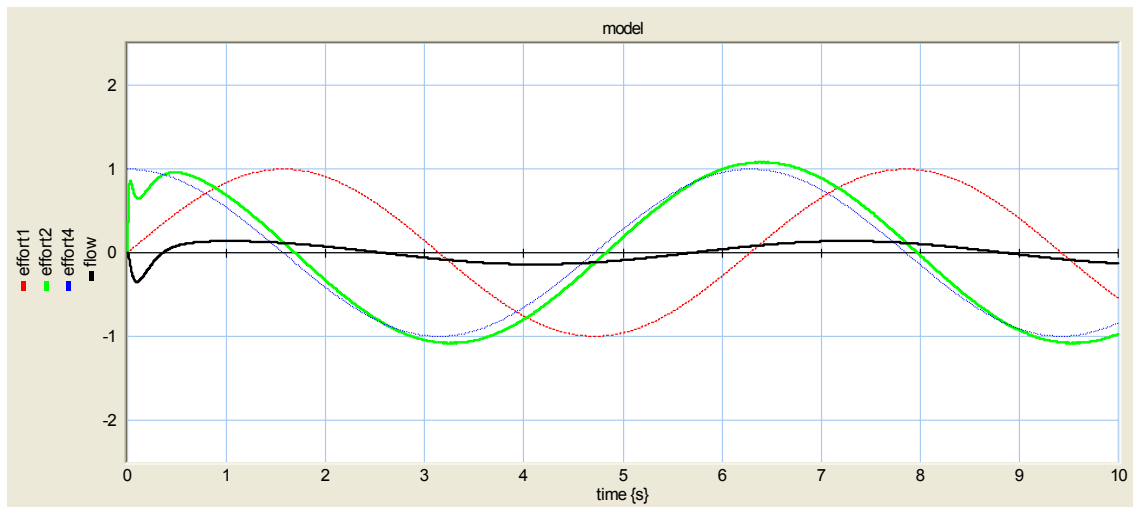Fig. 11: Theoretical Simulation Result

Fig. 12: Implemented Hyper-bond (Sampling Rate 1000 Hz)

Applications

Sensing the effort and generating a real flow may be used to continue one phenomenon from one media into another, just in the sense of a functional continuation as we know it from mathematics of functional analysis, but we also may modify this continuation in an arbitrary sense given by some virtual constraints or boundary conditions. This can be useful for remote operation in flexible virtual-real environments. In fig. 13-14 the model for a simple force-feedback system is presented. A momentum handle senses a force (effort) between a driving pulley and a pulley blocked by a one-directional worm-gear. For simplicity it is represented by a TF-node, but for our dynamic studies we used the 20-sim worm-gear backlash implementation. The force-signal is used within the control programme of the virtual world to calculate a resulting force depending on the other virtual processes (in fig. 13 only represented as a constant). The resulting force signal is then used to drive a motor connected to the second pulley via worm-gear in a flow-controlling way. It is obvious that this closed loop control depends very much on the time characteristics of the application (Se), the network-transport delay-time (A/D to D/A) and various inductivities, resistances and capacities.
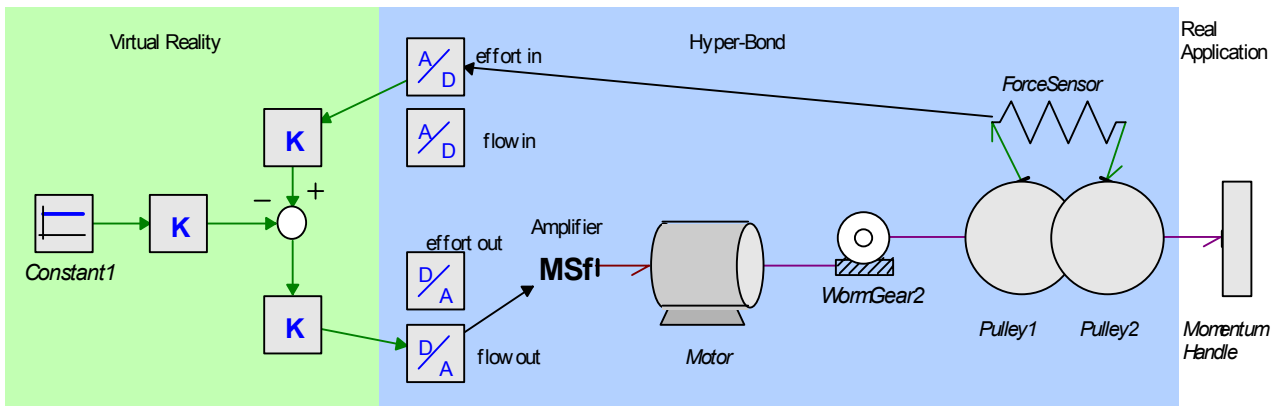
Fig. 13: Torque-sensing and speed-generation
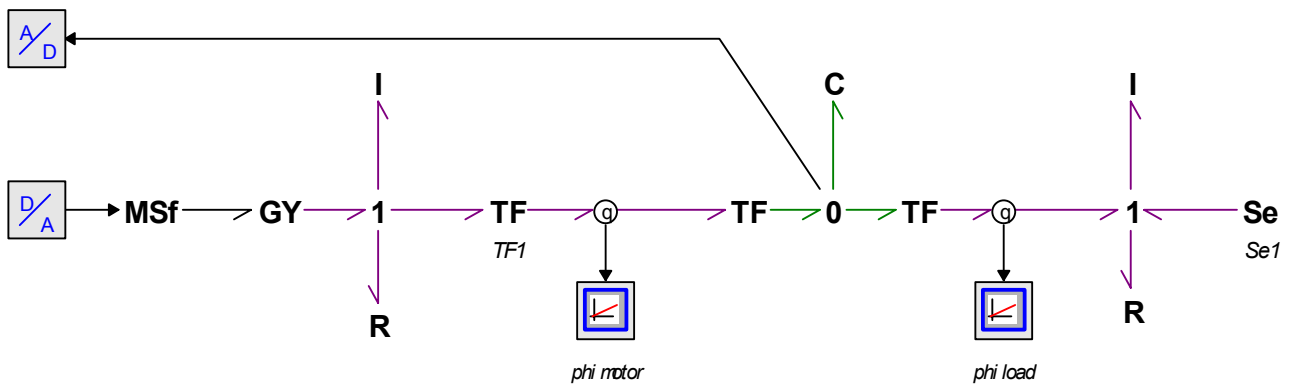
Fig. 14: Bond-graph for of a torque-sensing and speed-generation

As the bond-graph is a representation in a unified way, we can implement this application it in all other physical domains with the same dynamic characteristics if we have adequate sensor/generator devices: in translational movement with force and speed, in pneumatics with pressure and flow, in electrical networks with electrical potential and current, in thermodynamics with temperature and heat-flow.
The following examples are taken from Karnopp et al (1990) and converted to two systems connected by hyper-bonds.

Fig. 15: Electrical Network of RCI (all =1, I1=100) (Example 4.1)
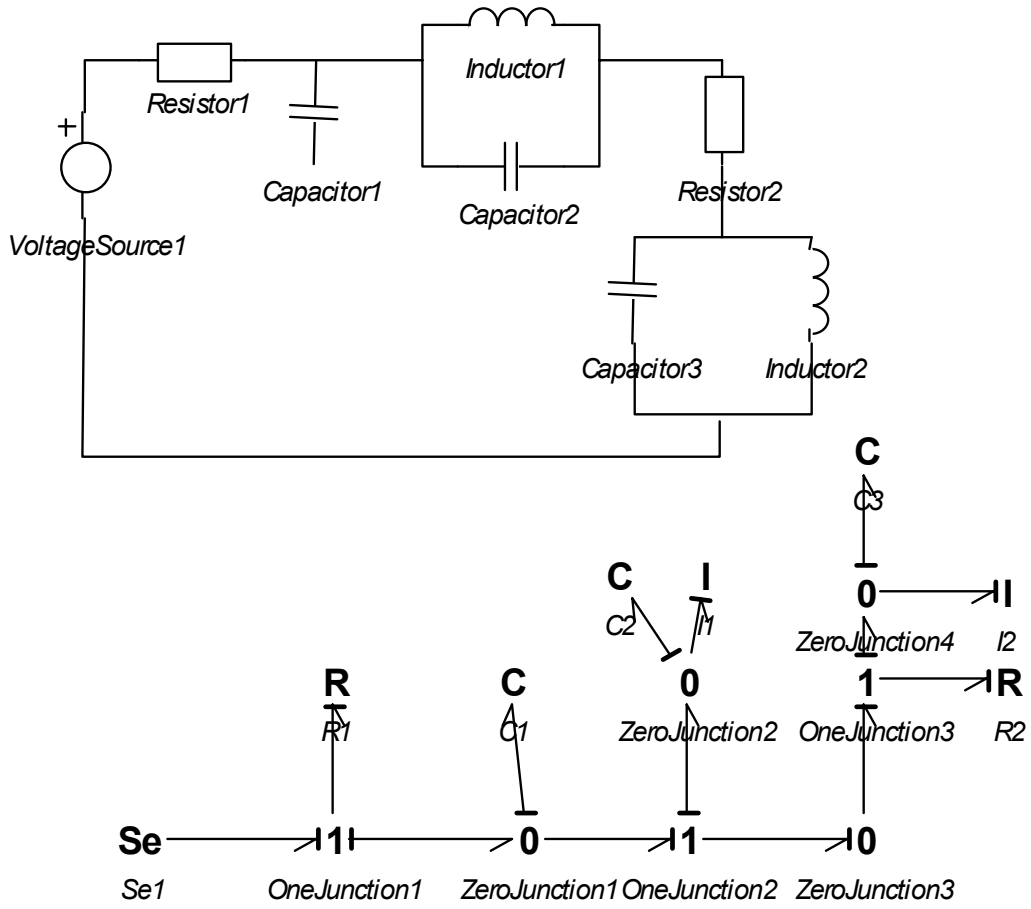
20-sim 3.1 demo (c) CLP 2000
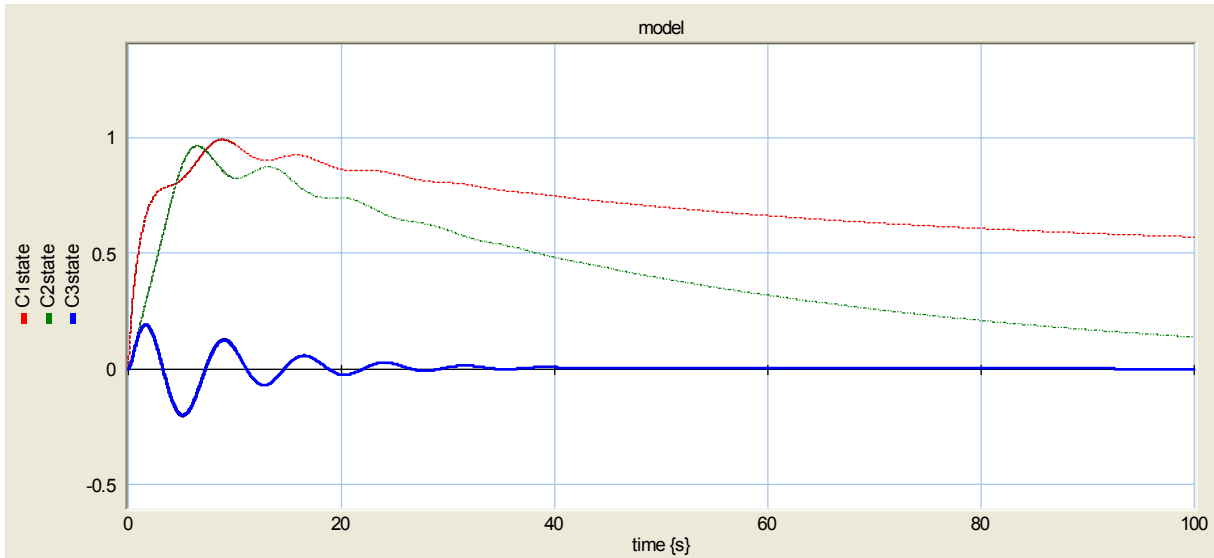
Fig. 16: Behaviour of original system

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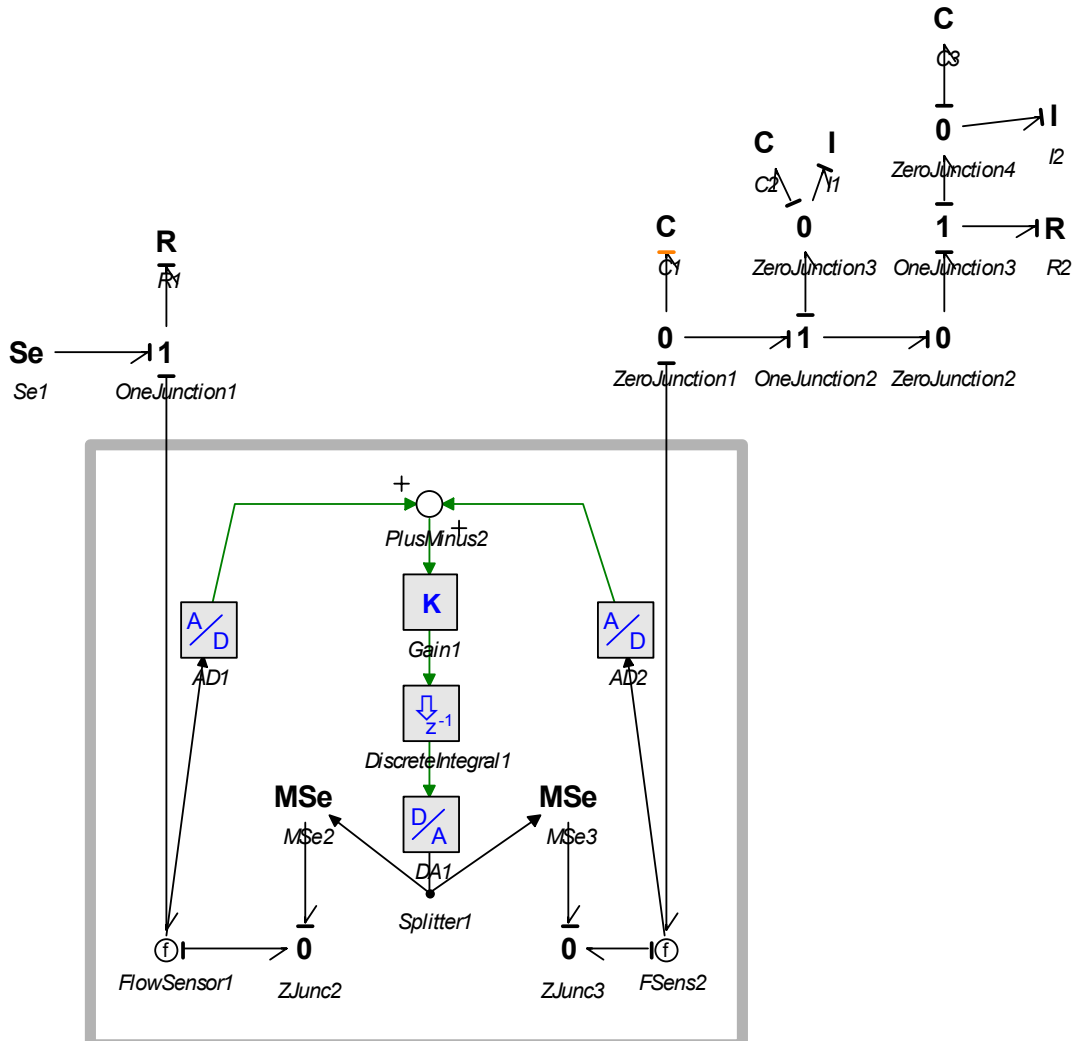
Fig. 17: Bond-graph connection of two subsystems
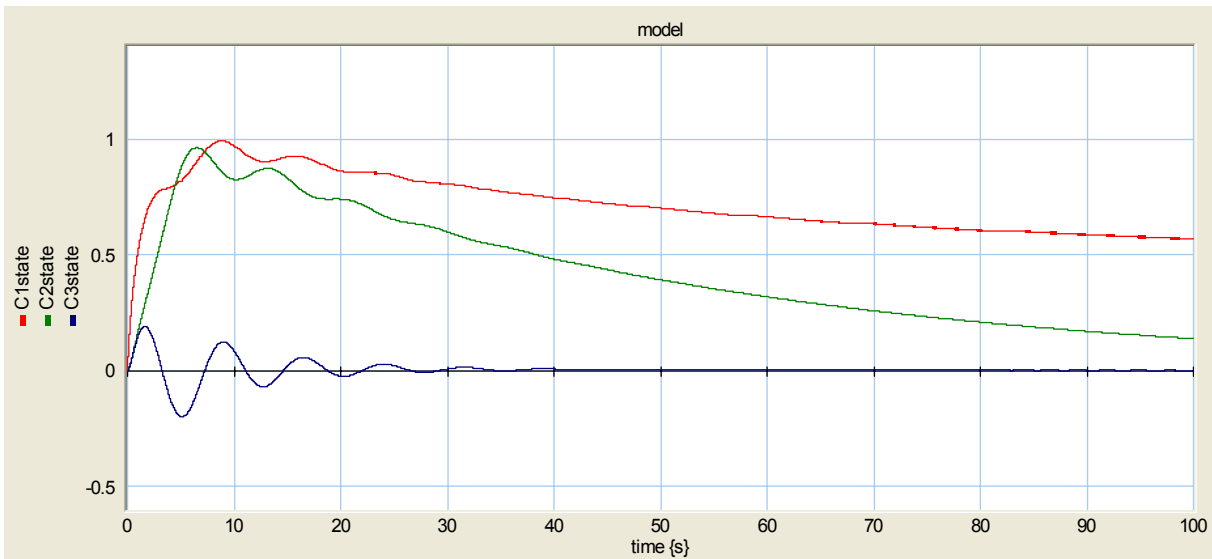
Fig. 18: Behaviour of Hyper-bond System (Gain K=1, Sampling Rate = 1000 Hz))

Karnopp Experiment 4.11
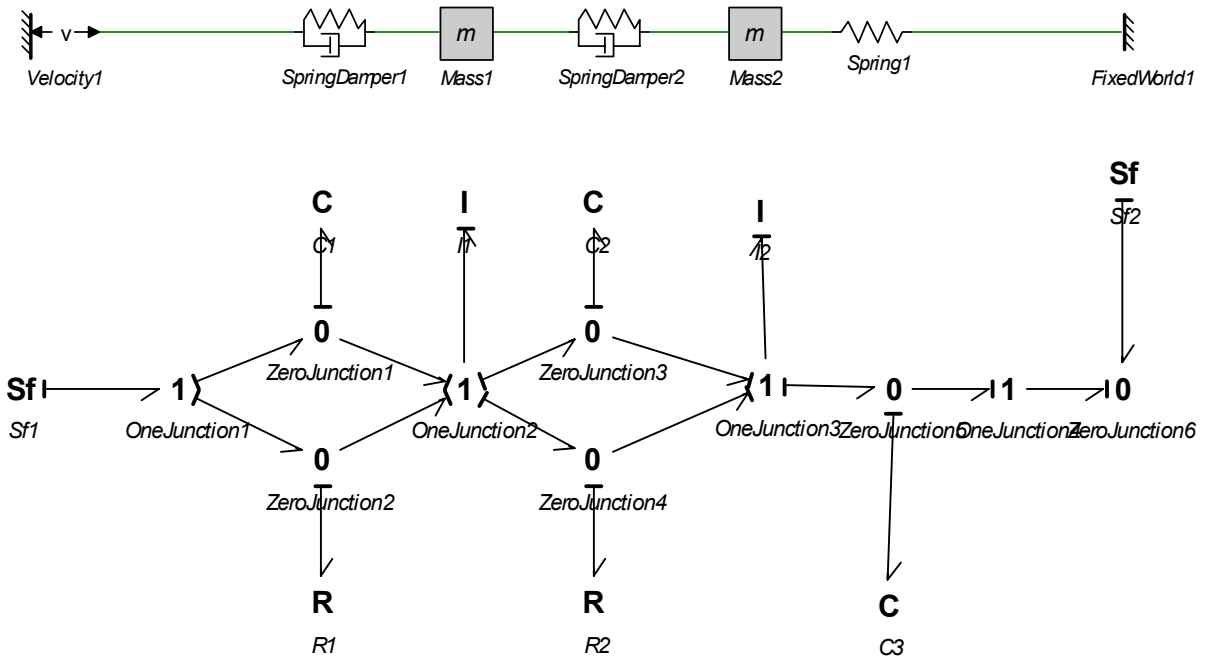
Fig. 19: Two-Mass Spring-Damping System (Example 4.11)
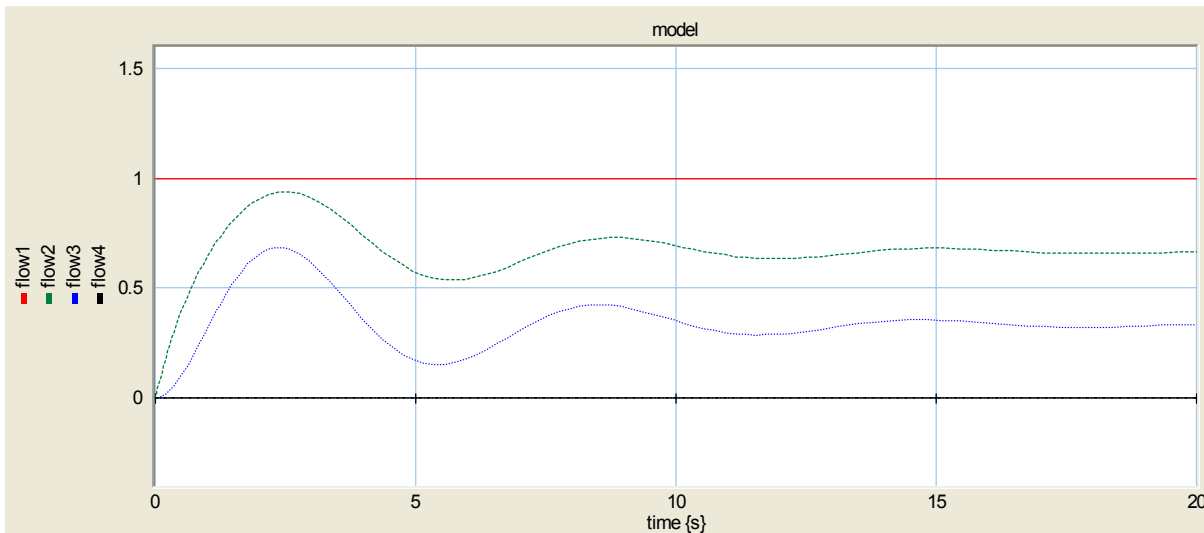
Fig. 20: Behaviour of original System
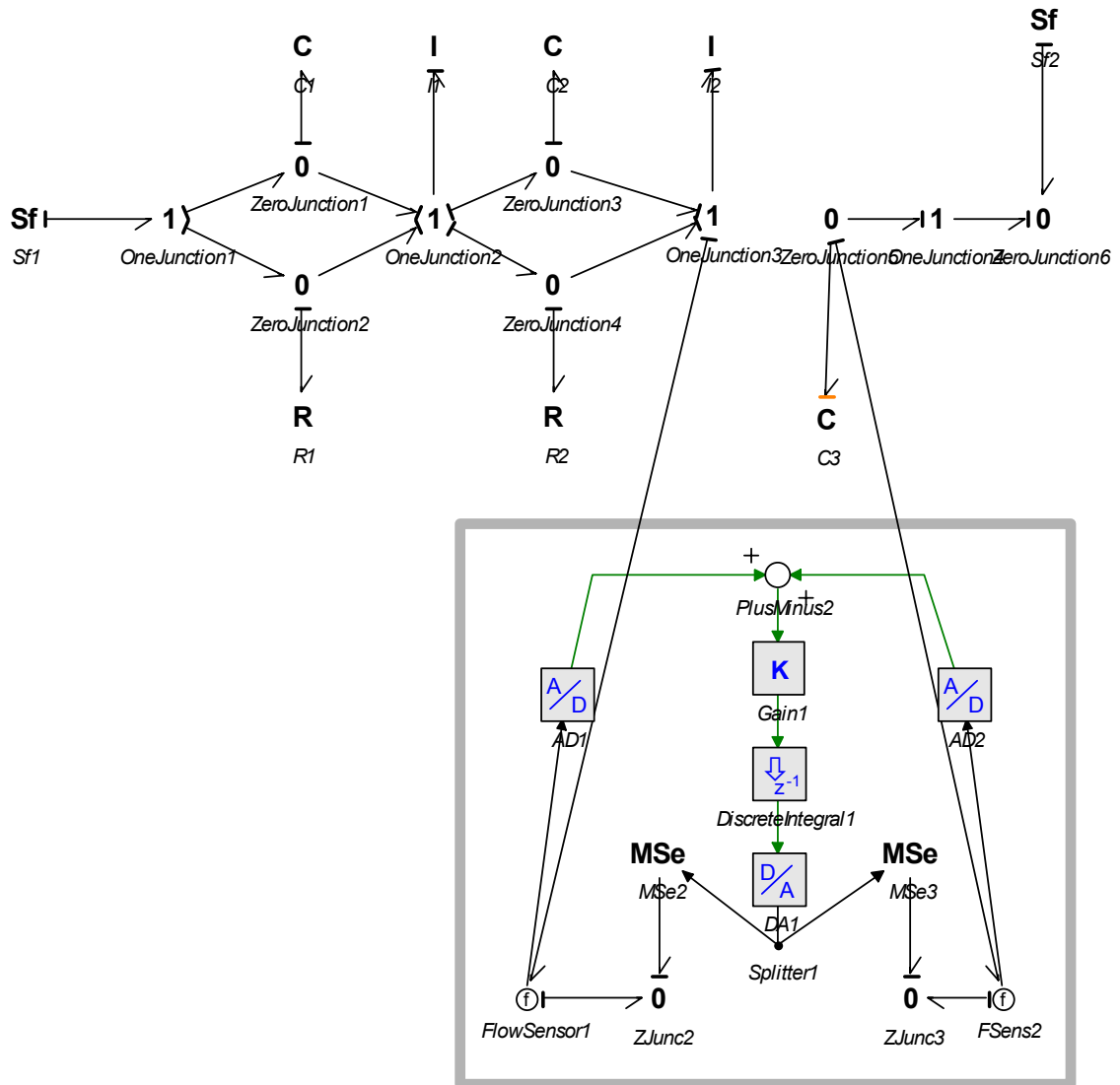
Fig. 21: Hyper-bond Implementation
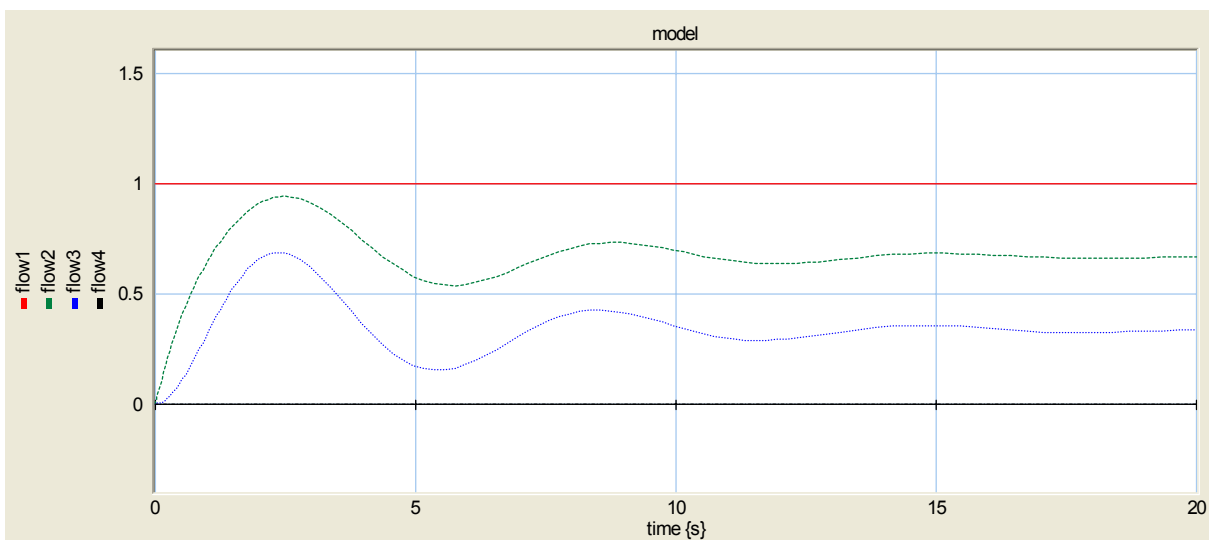
Fig. 22: Hyper-bond behaviour

There are however examples where the actual hyper-bond implementation yields a different behaviour.
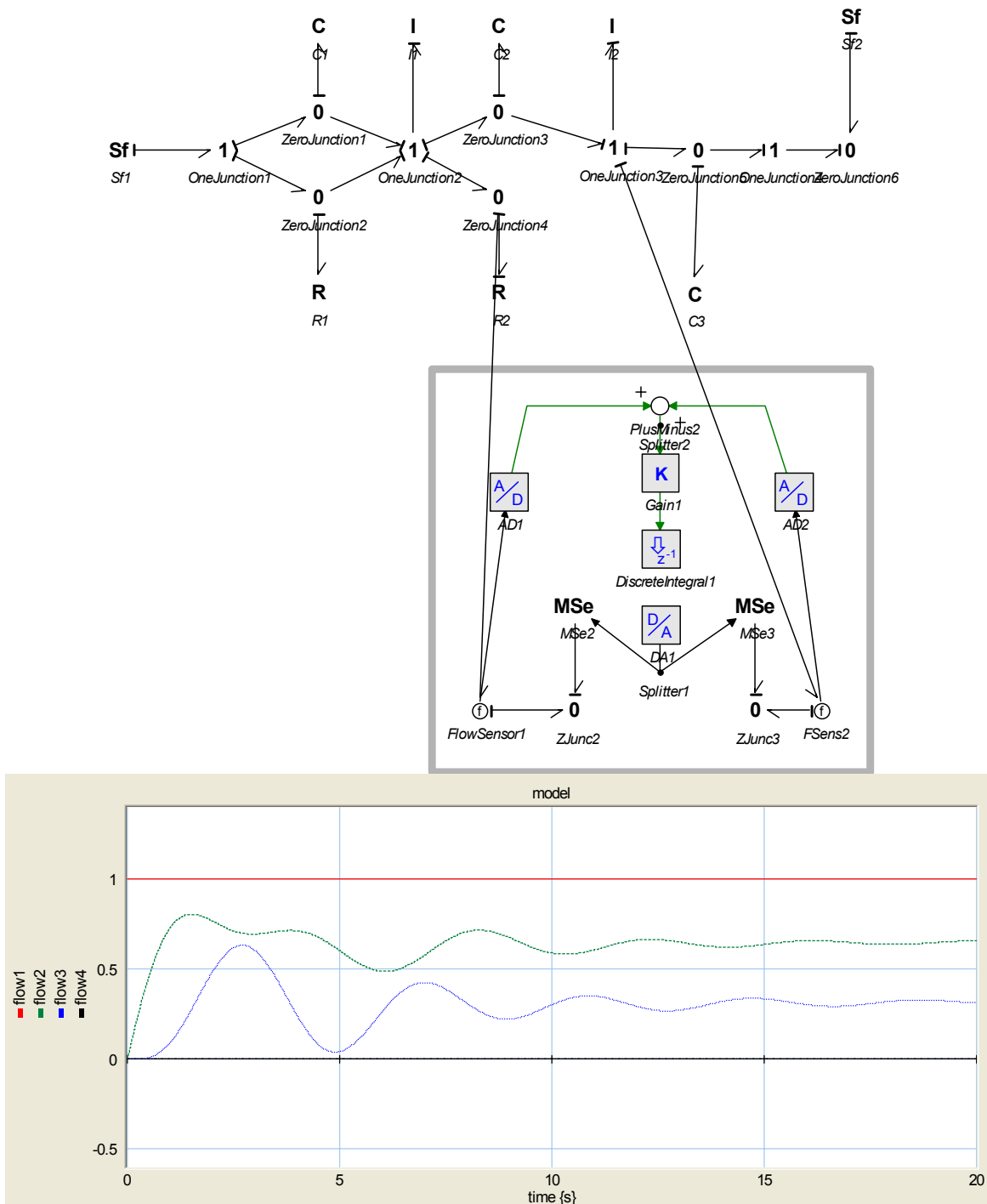
Fig. 23: Disconnecting a parallel flow and the Hyper-bond Behaviour

Slightly changing the formal representation of the original model resolves this problem.

Fig. 24: Correct Hyper-bond integration

Fig. 25: Correct solution with K=10, Sampling Rate 0.001

Fig. 26: Hiding the Hyper-Bond in a Sub-model

The Hyper-Bond implementation can be stored in a sub-model and used as any other sub-model with two energy-ports.

Results and Conclusion

A theoretical foundation of hyper-bonds has been given and some applications were presented. A general interface concept to merge physical phenomena and information flows as a continuation or modification is a powerful means to design mixed reality environments beyond those approaches which reduce the mixture to an overlay of reality and image-projections.

Two major problems can be identified so far:
1. To integrate hyper-bond simulation functionality into interactive virtual components representing real objects is still an open issue. Tools like 20-sim support C-code exportation and dll-interfacing, but it is not a trivial problem to merge various time characteristics of numerical integration methods within a stiff or discontinuous system.
2. The adequateness and quality of the hyper-bond implementation depends on the dynamics of the connected systems. Although it is not necessary to have full knowledge about the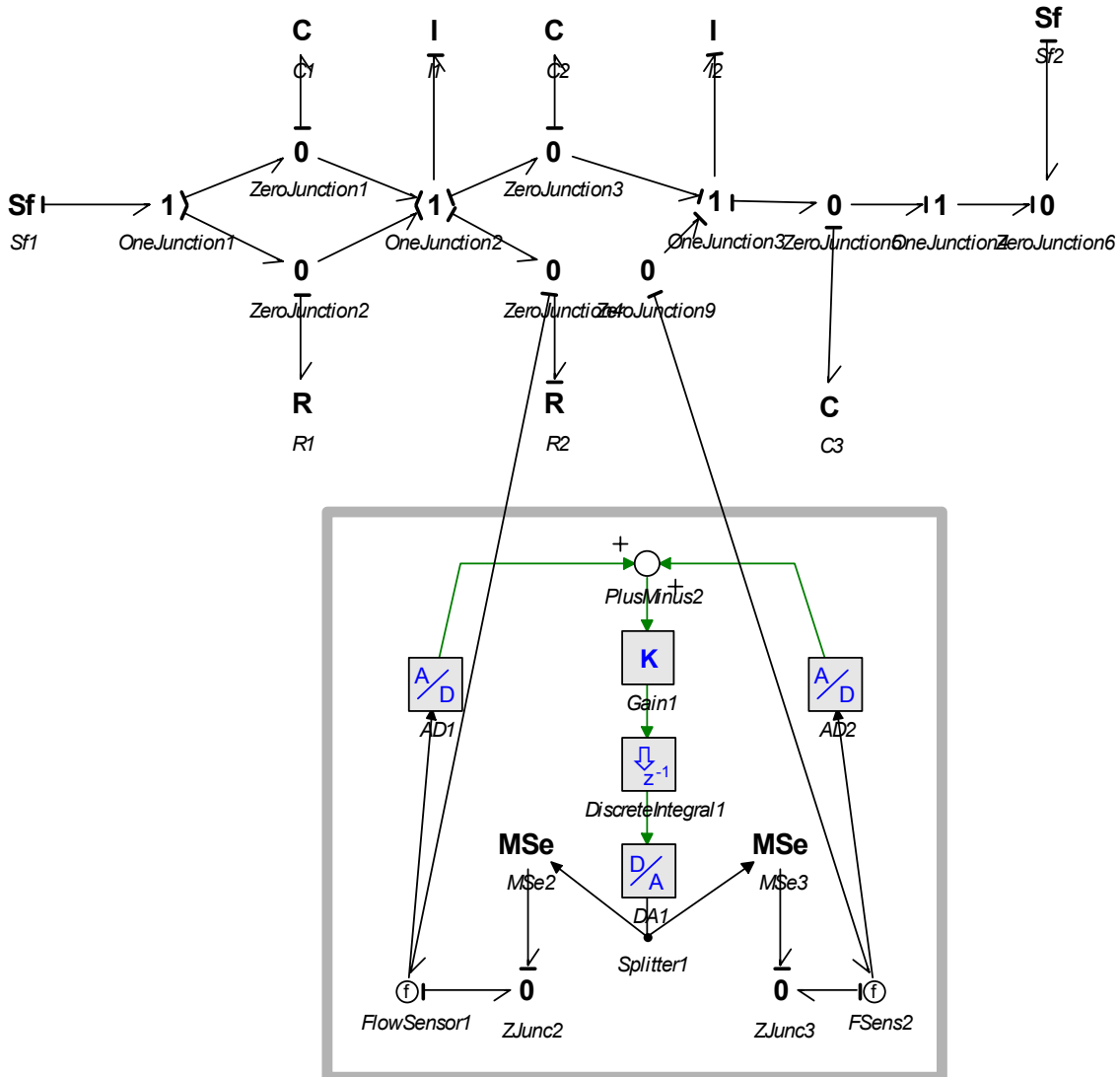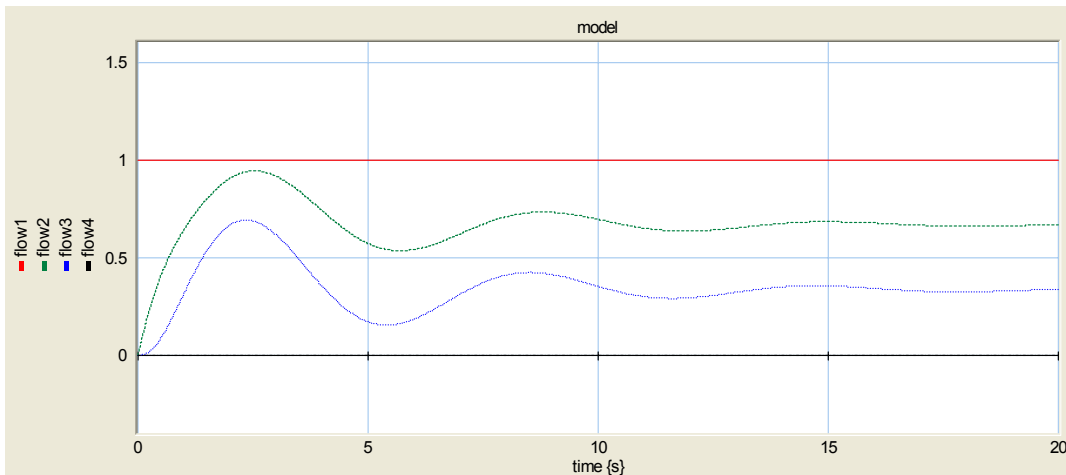 connected systems, it is necessary to have some boundary values of relevant frequencies. Or in other words, having a certain hyper-bond implementation, a certain class of behaviors can be translated.

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